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Krang: Center of Mass Estimation

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1 Introduction

The goal of this report is to delineate the mass and the center of mass measurements for the Krang model. We will separate Krang into several sections and compute the center of mass of each section within its frame of reference. Finally, we will compute the entire center of mass as a function of the joint angles and the body pitch angle. The sections are:

1. Base: Excluding wheels, all the parts until the spine plates.
2. Spine: From the spine plates until the shoulder bracket.
3. Shoulder bracket: Includes the bracket, the two arm base modules and the Kinect base.
4. Kinect: The Kinect itself and the supporting plate.

along with the arm groups, where we just delineate them for the left arm, and named for the joint that they move with:

5. Joint1: Bracket 1 and vertical motor 1
6. Joint2: Bracket 2 and horizontal motor 2
7. Joint3: Bracket 3 and vertical motor 2
8. Joint4: Bracket 4 and horizontal motor 3
9. Joint5: Bracket 5 and vertical motor 3
10. Joint6: Bracket 6, horizontal motor 4, netcanft card
11. Joint7: Force torque cap/extension, gripper

2 Section 1: Base

In analyzing the base section, we first removed the small parts and measured the *core base* which includes the wheel gearboxes, the chassis, the blue box and etc. Then, we also measured the smaller parts such as the batteries, battery straps, vision and main computers and etc. Here is a detailed list of the parts:

1. Core base
2. Batteries (x8)
3. Front and rear straps
4. Front/rear mats (between battery and straps)
5. Main and vision computer
6. Waist modules
7. Waist plate
8. Waist brackets
9. Waist bracket spacers

In order to express the COM of the entire section we will first choose a frame of refernce that is fixed on a convenient point on the section. This is called the *"Section Frame of Reference"*. In order to calculate the COM of the entire section we will use the well known equation:

$$X_{COM} = \frac{\sum m_i X_{s(i)}}{\sum m_i} \tag{1}$$

where $X_{COM} = (x, y, z)_{COM}$ is the COM of the entire section expressed in section frame of reference, m_i is the mass of the ith part and $X_{s(i)} = (x_s, y_s, z_s)_i$ is the COM of the ith part expressed in the section frame of reference (indicated by subscript s). We call it *"Section COM"* of the ith part. The center of mass of each individual part is originally measured and expressed in another frame of reference, called the *"Part Frame of Reference"* and we name this COM as *"Local COM"* of the part. The origin of this frame of reference is at some convenient point on the part, called *"Part Origin"*. The axes of the part frame of reference are always chosen to be parallel to those of the section frame of reference.

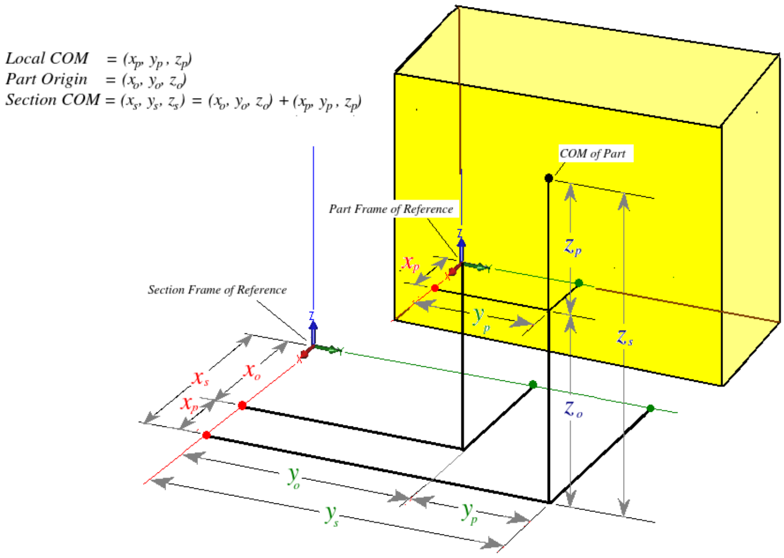


Figure 1: Explaining terms in the COM Estimation Table of each section

If $X_{o(i)} = (x_o, y_o, z_o)_i$ represents the coordinates of the part origin of the ith part expressed in section frame of reference, and $X_{p(i)} = (x_p, y_p, z_p)_i$ is the local COM of the part then (Figure 1):

$$X_{s(i)} = X_{o(i)} + X_{p(i)} \tag{2}$$
$$(x_s, y_s, z_s)_i = (x_o, y_o, z_o)_i + (x_p, y_p, z_p)_i \tag{3}$$

Hence it follows that the estimation of the center of mass of the entire section requires the knowledge of three items:

- Masses: The mass of each part m_i
- Local COMs: the center of mass of each part expressed in a convenient frame of reference on the part $X_{p(i)} = (x_p, y_p, z_p)_i$
- Part Origins: The coordinates of the origin of the part frame of reference expressed in section frame of reference $X_{o(i)} = (x_o, y_o, z_o)_i$.

Figure 2 shows the Part Origins of all the individual parts of the base section. The mass and Local COM of each part are determined by physical measurements using scales. This is laid down in the appendix at the end of the report.

Table 1 lists down all parts along with mass, local COM, part origin and section COM of each part. In the last row, the total mass of the section is mentioned along with the section COM calculated using equation 1.

In order to visually verify the calculation of the center of mass in table 1 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 3. The figure shows the scatter plot in both the front view and the (right) side view. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

2.1 Validation

In order to increase our confidence on the estimated center of mass, we measured the center of mass of the entire section. Figure 4 shows the raw experimental setup and measurements. The entire section

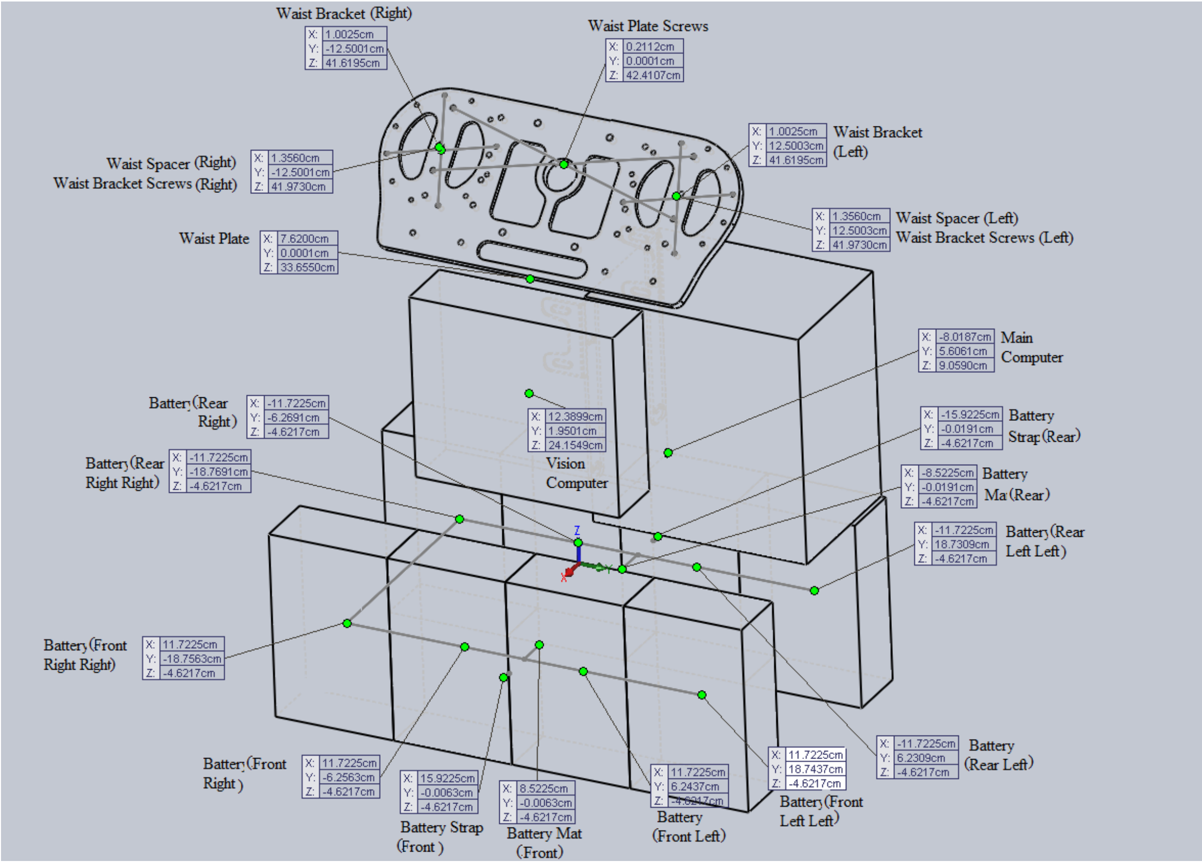


Figure 2: Part origins of base expressed in base section frame of reference. Part origin is the origin of the part coordinate system. The COM of individual part is expressed in part cooridnate system

Part	**Mass**	**Local COM**			**Part origin**			**Section COM**		
		x	y	z	x	y	z	x	y	z
Battery Front Left Left	2.134	0	0	3	11.7225	18.7437	-4.6217	11.7225	18.7437	-1.6217
Battery Front Left	2.134	0	0	3	11.7225	6.2437	-4.6217	11.7225	6.2437	-1.6217
Battery Front Right	2.134	0	0	3	11.7225	-6.2563	-4.6217	11.7225	-6.2563	-1.6217
Battery Front Right Right	2.134	0	0	3	11.7225	-18.7563	-4.6217	11.7225	-18.7563	-1.6217
Main Computer	6.34	7.4986	10.79	11.48	-8.0187	5.6061	9.059	-0.5201	16.3961	20.539
Vision Computer	1.64	0	-0.6951	0.5573	12.3899	1.9501	24.1549	12.3899	1.255	24.7122
Waist Plate	1.08	-5.54	0	6.16	7.62	0	33.655	2.08	0	39.815
Waist Bracket (Left)	0.473	3.98	4.93	3.98	1.0025	12.5003	41.6195	4.9825	17.4303	45.5995
Waist Bracket (Right)	0.48	3.98	-4.93	3.98	1.0025	-12.5003	41.6195	4.9825	-17.4303	45.5995
Battery Mat (Rear)	0.26	0	0	0	-8.5225	-0.0191	-4.6217	-8.5225	-0.0191	-4.6217
Battery Mat (Front)	0.26	0	0	0	8.5225	-0.0063	-4.6217	8.5225	-0.0063	-4.6217
Battery Strap (Rear)	0.5	0	0	0	-15.9225	-0.0191	-4.6217	-15.9225	-0.0191	-4.6217
Battery Strap (Front)	0.5	0	0	0	15.9225	-0.0063	-4.6217	15.9225	-0.0063	-4.6217
Waist Spacer (Left)	0.122	0	0	0	1.356	12.5003	41.973	1.356	12.5003	41.973
Waist Spacer (Right)	0.121	0	0	0	1.356	-12.5003	41.973	1.356	-12.5003	41.973
Waist Bracket Screws (Left)	0.046	0	0	0	1.356	12.5003	41.973	1.356	12.5003	41.973
Waist Bracket Screws (Right)	0.046	0	0	0	1.356	-12.5003	41.973	1.356	-12.5003	41.973
Waist Plate Screws	0.057	0	0	0	0.2112	0.0001	42.4107	0.2112	0.0001	42.4107
Total	**75.767**							**-0.0628**	**0.1940**	**7.6721**

Table 1: COM Calculation of the Base

is placed simulatneously on two scales in three different orientation. In each orientation, the scales are placed along one of the three coordinates axes of the section frame of reference. This allows us to calculate the coordinate of the COM along each axes. Table 2 shows this calculation.

Comparing the physical measurement with the part-based estimation reveals that the difference

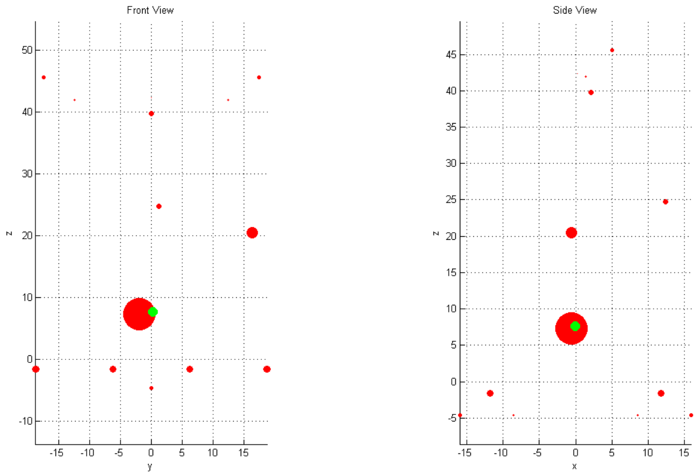


Figure 3: Visualizing the center of mass calculation of the base section with a scatter plot in thee front view and the side view

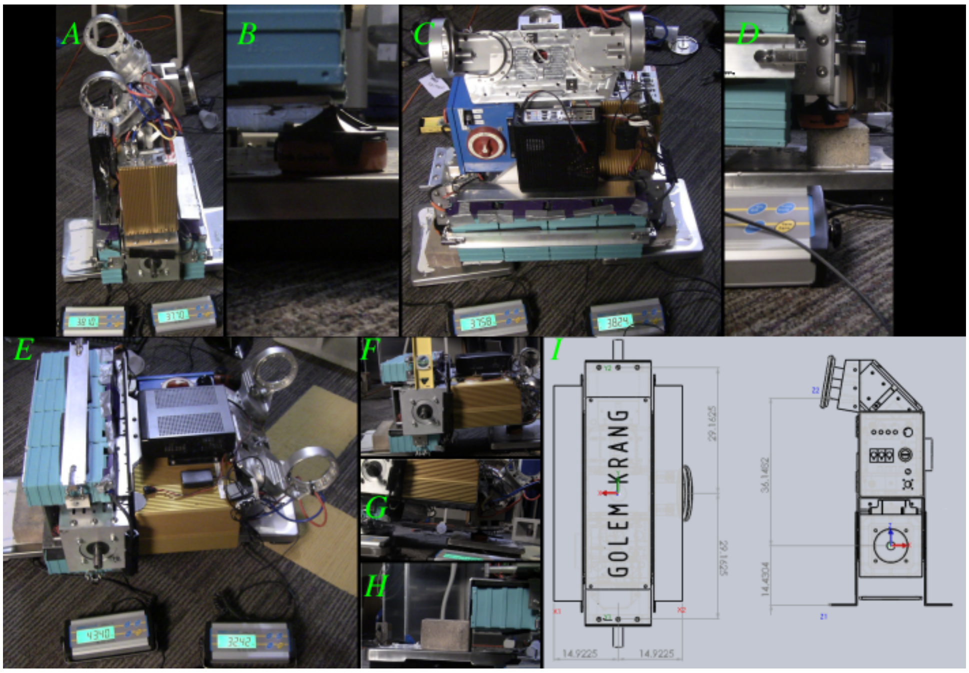


Figure 4: Measurements of the COM of the entire base section

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
x	38.1	37.7	14.9225	-14.9225	0.0787
y	37.58	38.24	-29.1625	29.1625	0.2539
z	43.4	32.42	-14.4304	36.1428	7.1966

Table 2: Meaurement of the COM of the entire base section

between the two is in the order of millimeters.

3 Section 2: Spine

The measurement of the COM of the spine section is done in the same way we carried out that for the base section. We took the spine apart into the following pieces:

1. Waist Motor (× 2)
2. Cap of Waist Motor (× 2)
3. Side Plate (× 2)
4. Tube (plus a small Gantry hook)
5. End-Cap
6. Bolt (× 2)
7. Plate Screws
8. Waist Motor-to-Bracket Screws
9. Waist Motor-to-Plate Screws
10. Capacitor
11. Wires
12. Rubber rings for wires tube wall (× 3)

Following the same principle as described in the last section, we determine the part origins using the SolidWorks model (Figure 5). The mass and local COM of each part is measured physically, the details of which are found in the appendix. The details are listed down in table 3. The last row of the table shows the estimated COM of the spine calculated by plugging the part data from the table in equation 1.

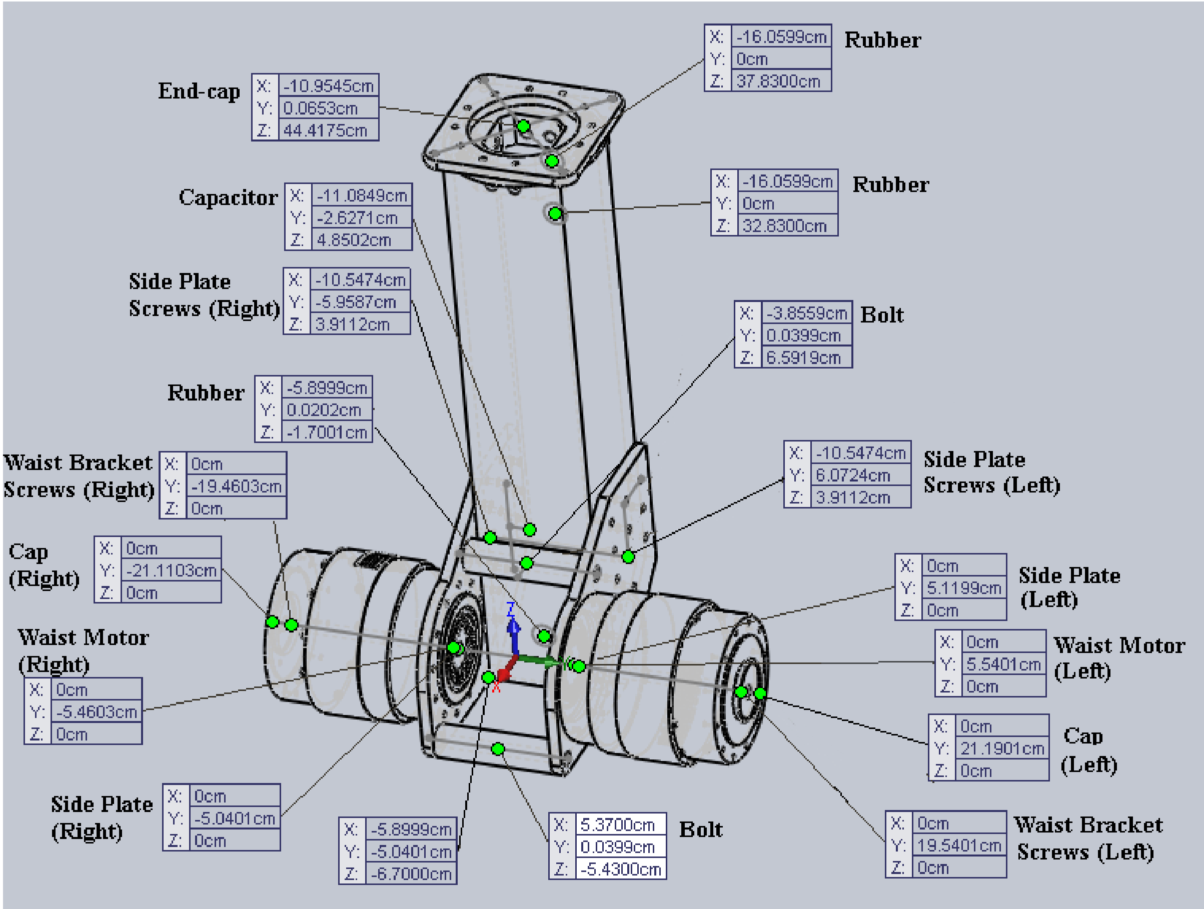


Figure 5: Part origins of spine expressed in spine section frame of reference. Part origin is the origin of the part coordinate system. The COM of individual part is expressed in part cooridnate system

Part	Mass	Local COM			Part origin			Section COM		
		x	y	z	x	y	z	x	y	z
Side Plate	1.026	-7.233	0	2.479	0	0	0	-7.233	0	2.479
Schunk Modules	6.614	0	0	0	0	0	0	0	0	0
Tube Gantry	3.453	-4.841	5.08	26.216	-5.8999	-5.0401	-6.7	-10.7409	0.0399	19.516
End-Cap	0.76	0	0	-1.45	-10.9545	0.0653	44.4175	-10.9545	0.0653	42.9675
Caps	0.056	0	0	0	0	0	0	0	0	0
Bolt1	0.264	0	0	0	-3.8559	0	6.5919	-3.8559	0	6.5919
Bolt2	0.264	0	0	0	5.37	0	-5.43	5.37	0	-5.43
Rubber1	0.0097	0	0	0	-16.0599	0	37.83	-16.0599	0	37.83
Rubber2	0.0097	0	0	0	-16.0599	0	32.83	-16.0599	0	32.83
Rubber3	0.0097	0	0	0	-5.8999	0	-1.7001	-5.8999	0	-1.7001
Plate Screws	0.108	0	0	0	-10.5474	0	3.9112	-10.5474	0	3.9112
Schunk Bracket Screws	0.073	0	0	0	0	0	0	0	0	0
Schunk Plate Screws	0.083	0	0	0	0	0	0	0	0	0
Capacitor	0.162	0	0	0	-11.0849	-2.6271	4.8502	-11.0849	-2.6271	4.8502
Wires	1.114	-14.3664	0.6479	7.1952	0	0	0	-14.3664	0.6479	7.1952
Total	**14.006**							**-5.1222**	**0.0345**	**8.0526**

Table 3: COM Calculation of the Spine

In order to visually verify the calculation of the center of mass in table 3 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 6. The figure shows the scatter plot in both the front view and the (right) side view. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

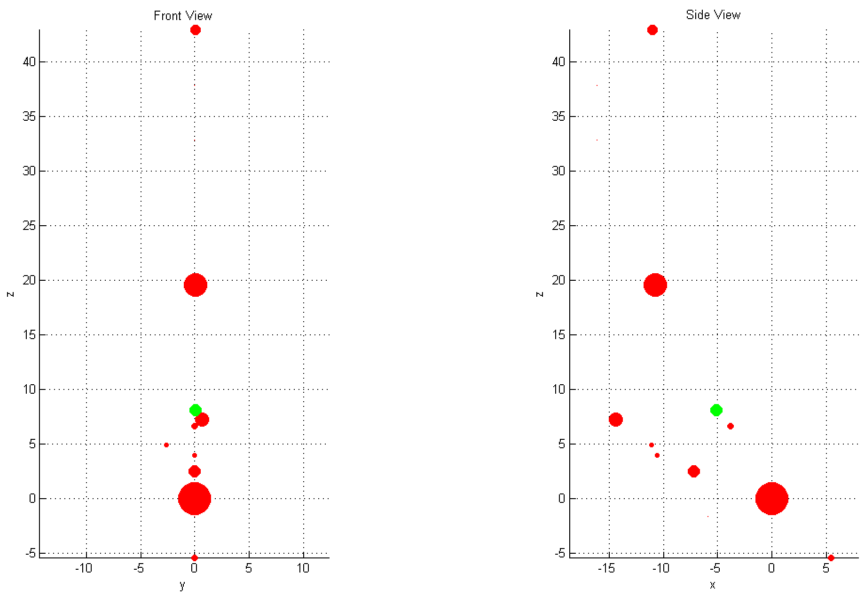


Figure 6: Visualizing the center of mass calculation of the spine section with a scatter plot in thee front view and the side view

3.1 Validation

In order to increase our confidence on the estimated center of mass, we measured the center of mass of the entire section. Figure 7 shows the raw experimental setup and measurements. The entire section is placed simulatneously on two scales in three different orientation. In each orientation, the scales are placed along one of the three coordinates axes of the section frame of reference. This allows us to calculate the coordinate of the COM along each axes. Table 4 shows this calculation.

Figure 7: COM Measurement of the entire spine section

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
x	11.36	2.38	-7.8599	6.64	-5.3483
y	6.78	6.86	-6.0125	6.0125	0.0353
z	2.52	11.18	44.4175	0.35	8.4558

Table 4: Meaurement of the COM of the entire spine section

4 Section 3: Shoulder Bracket

The Shoulder Bracket is the third section of the robot. The list of parts of the section is as under:

1. Bracket
2. Torso
3. Kinect Holder
4. long Screws
5. Top Plate Screws
6. Bottom Plate Screws
7. Torso Screws
8. Kinect Screws

Figure 8 shows the section frame of reference and the part origins expressed in this frame for each part. Masses and local COMs for the parts will be found in the appendix. Table 5 lists down the values, and shows the calculation of the section COM based on equation 1. The last row shows the total mass and the center of mass of the section.

Part	**Mass**	**Local COM**			**Part origin**			**Section COM**		
		x	**y**	**z**	**x**	**y**	**z**	**x**	**y**	**z**
Bracket	2.684	0	-1.6436	-0.0572	0	15.2927	-0.0036	0	13.6491	-0.0608
Torso	3.26	0	1.0335	0	0	0	0	0	1.0335	0
Kinect Holder	0.36	0	1	-1	0	22.93	-9.1313	0	23.93	-10.1313
long Screws	0.132	0	0	0	0	0	0	0	0	0
Top Plate Screws	0.026	0	0	0	0	22.6125	0	0	22.6125	0
Bottom Plate Screws	0.019	0	0	0	0	8.295	0	0	8.295	0
Torso Screws	0.042	0	0	0	0	8.295	0	0	8.295	0
Kinect Screws	0.01	0	0	0	0	22.93	-9.1313	0	22.93	-9.1313
Total	**6.533**							**0.0000**	**7.6445**	**-0.5972**

Table 5: COM Calculation of the Bracket

In order to visually verify the calculation of the center of mass in table 5 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 9. The figure shows the scatter plot in both the front view and the (right) side view. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

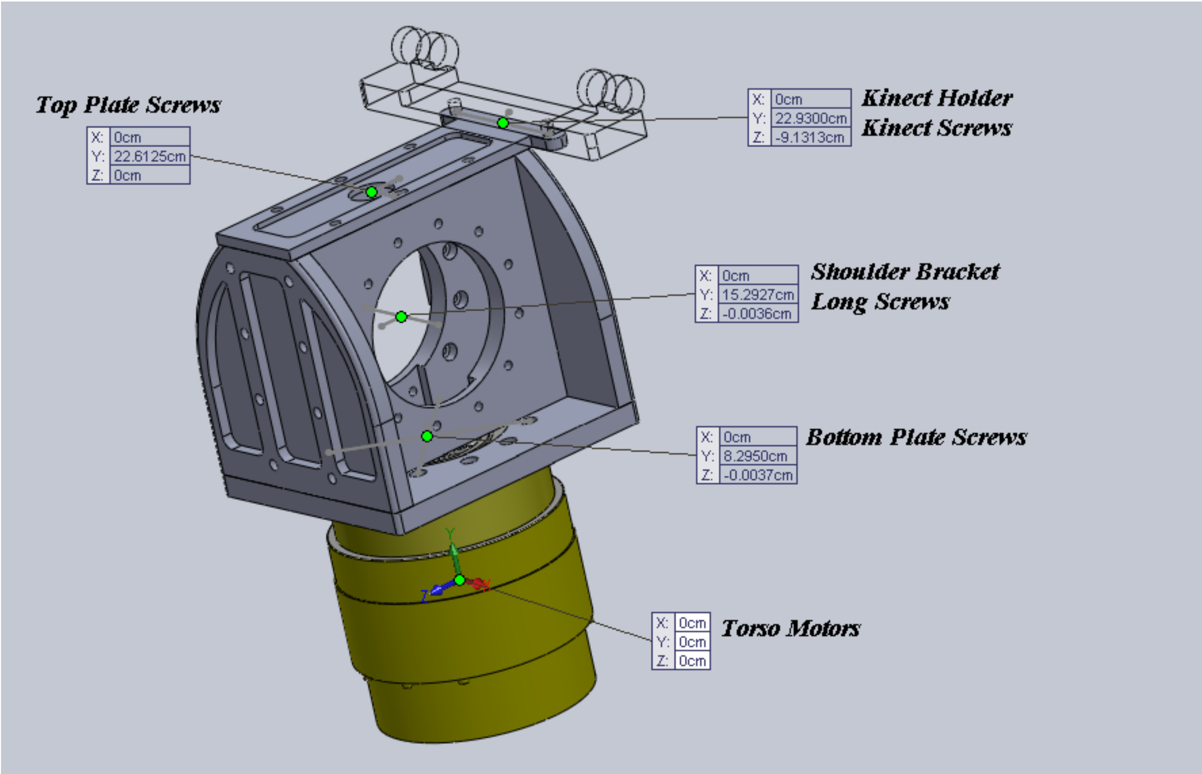


Figure 8: Part origins of Bracket expressed in bracket section frame of reference. Part origin is the origin of the part coordinate system. The COM of individual part is expressed in part cooridnate system

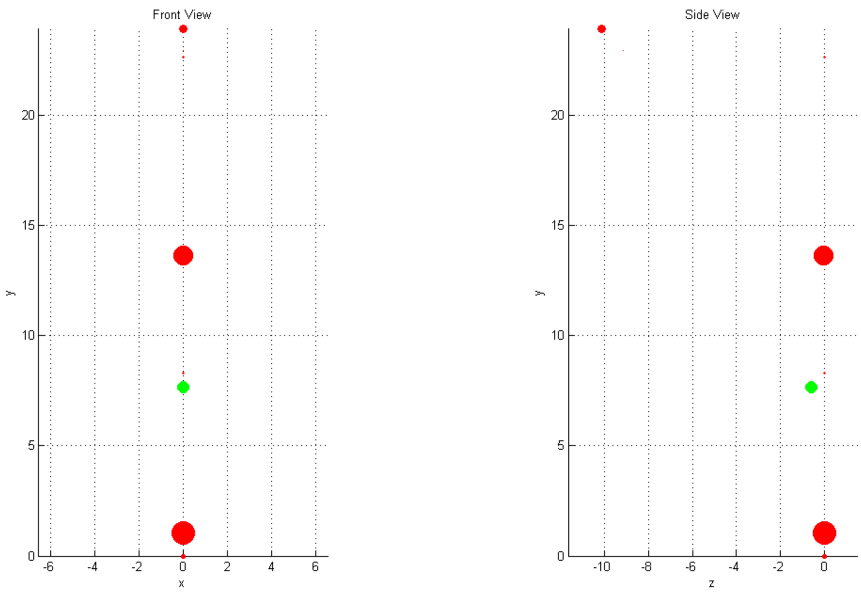


Figure 9: Visualizing the center of mass calculation of the bracket section with a scatter plot in thee front view and the side view

4.1 Validation

In order to increase our confidence on the estimated center of mass, we measured the center of mass of the entire section. Figure 10 shows the raw experimental setup and measurements. The entire section is placed simulatneously on two scales in two different orientation. In each orientation, the scales are placed along one of the two coordinates axes (y- ans z-) of the section frame of reference. Due to symmetry thee is no need to evaluate the coordinate along x-axis. This allows us to calculate the coordinate of the COM along each axes. Table 6 shows this calculation.

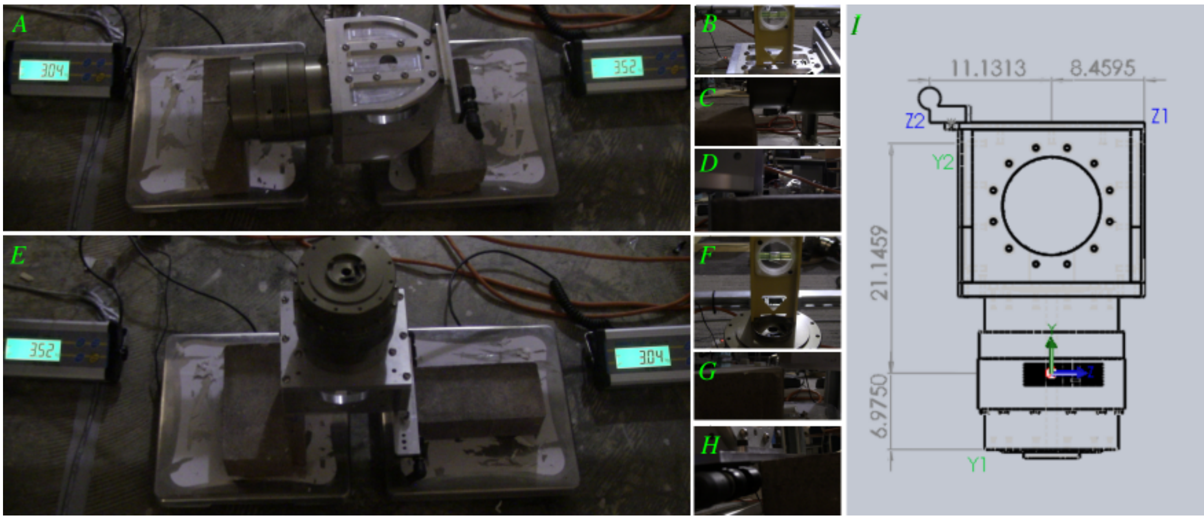


Figure 10: COM Measurement of the entire bracket section

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
y	3.04	3.52	-6.975	21.1459	8.1142
z	3.52	3.04	8.4595	-11.1313	-0.6191

Table 6: Meaurement of the COM of the entire bracket section

5 Section 4: Arm Joint 1

Two arms are mounted on the shoulder bracket that was discussed in the previous section. Each arm consists of seven sections. The two arms are identical, so, choosing similar section frames of reference for each arm will allow us to study only the COM of one arm and all numbers will apply directly to the other arm. We now start with the first joint of the arm. It consists of the following parts:

1. Motor M1
2. Connector Bracket C12
3. M1-C12 Screws
4. C12-M2 Screws
5. Cap C12-M2
6. Wires through M1

Figure 11 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 7 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

In order to visually verify the calculation of the center of mass in table 7 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 12. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

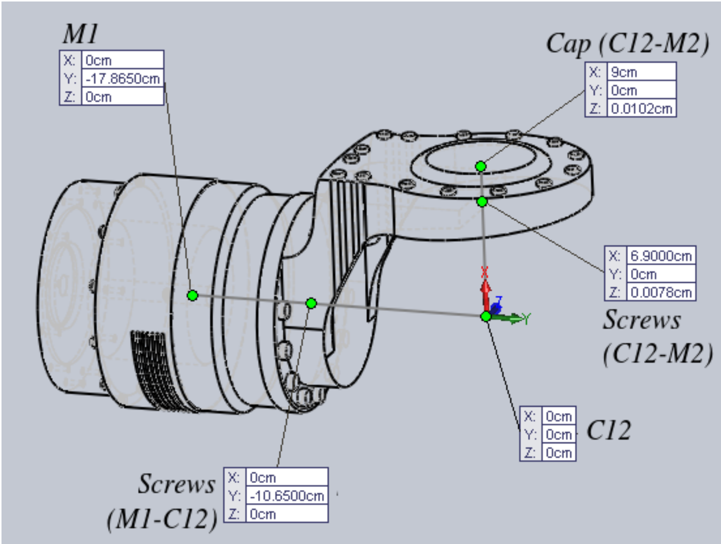


Figure 11: Part origins of Arm Section 1

Part	Mass	Local COM			Part origin			Section COM		
		x	y	z	x	y	z	x	y	z
M1	3.35	0	0	0	0	-17.865	0	0	-17.865	0
C12	0.486	4.32	-5.63	0	0	0	0	4.32	-5.63	0
M1-C12 Screws	0.0345	0	0	0	0	-10.65	0	0	-10.65	0
C12-M2 Screws	0.0345	0	0	0	6.9	0	0	6.9	0	0
Cap	0.029	0	0	0	9	0	0	9	0	0
Wires	0.018	0	0	0	0	-17.865	0	0	-17.865	0
Total	**3.952**							**0.6575**	**-16.0104**	**0.0000**

Table 7: COM Calculation of the Arm Section 1

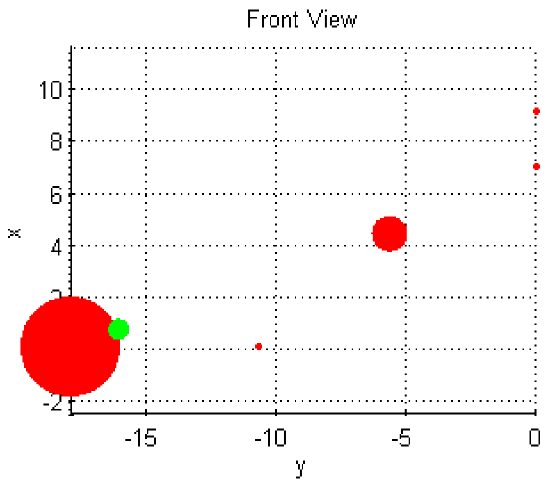


Figure 12: Visualizing the center of mass calculation of the Arm section 1 with a scatter plot in the front view

6 Section 5: Arm Joint 2

The second joint of the arm consists of the following parts:

1. Motor M2
2. Connector Bracket C23
3. M2-C23 Screws
4. C23-M3 Screws
5. Cap M2-C23
6. Wires through M2

Figure 13 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 8 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

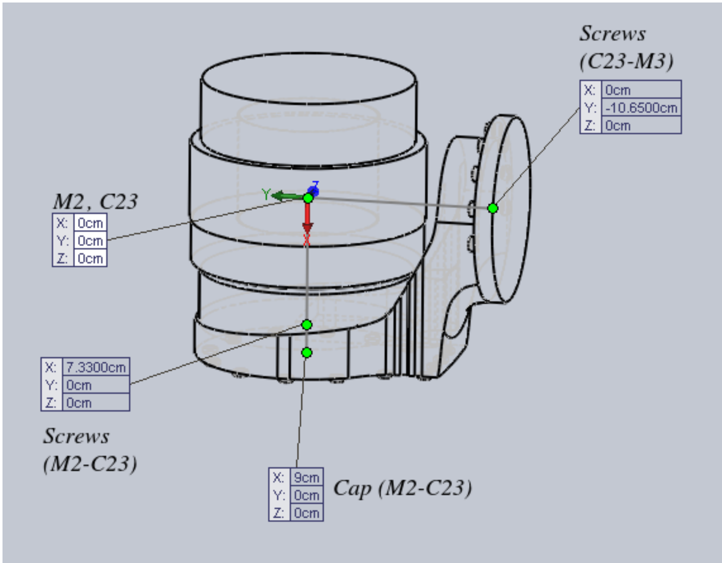


Figure 13: Part origins of Arm Section 2

Part	Mass	Local COM			Part origin			Section COM		
		x	y	z	x	y	z	x	y	z
M2	3.35	0	0	0	0	0	0	0	0	0
C23	0.454	4.73	-5.03	0	0	0	0	4.73	-5.03	0
M2-C23 Screws	0.0345	0	0	0	7.33	0	0	7.33	0	0
C23-M3 Screws	0.0345	0	0	0	0	-10.65	0	0	-10.65	0
Cap	0.034	0	0	0	9	0	0	9	0	0
Wires	0.018	0	0	0	0	0	0	0	0	0
Total	**3.925**							**0.6895**	**-0.6754**	**0.0000**

Table 8: COM Calculation of the Arm Section 2

In order to visually verify the calculation of the center of mass in table 8 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 14. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

7 Section 6: Arm Joint 3

The third joint of the arm consists of the following parts:

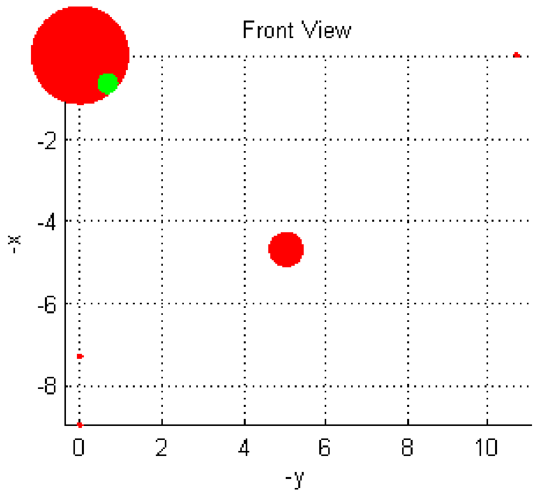


Figure 14: Visualizing the center of mass calculation of the Arm section 2 with a scatter plot in the front view

1. Motor M3
2. Connector Bracket C34
3. M3-C34 Screws
4. C34-M4 Screws
5. Cap C34-M4
6. Wires through M3

Figure 15 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 9 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

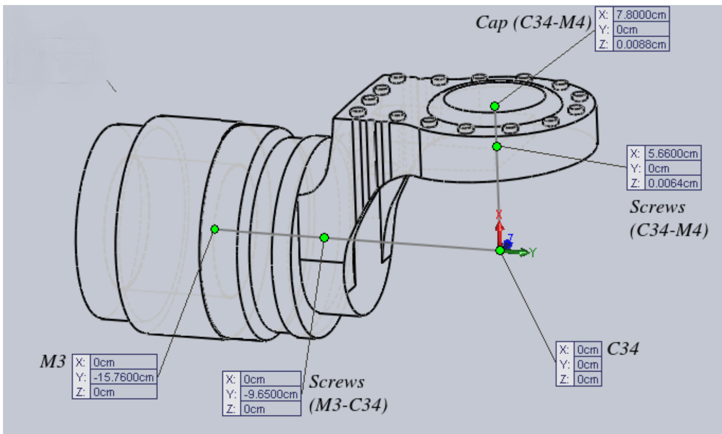


Figure 15: Part origins of Arm Section 3

In order to visually verify the calculation of the center of mass in table 9 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 16. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

Part	Mass	Local COM			Part origin			Section COM		
		x	y	z	x	y	z	x	y	z
M3	1.931	0	0	0	0	-15.78	0	0	-15.78	0
C34	0.368	3.68	-5.15	0	0	0	0	3.68	-5.15	0
M3-C34 Screws	0.0192	0	0	0	0	-9.65	0	0	-9.65	0
C34-M4 Screws	0.0192	0	0	0	5.66	0	0	5.66	0	0
Cap	0.021	0	0	0	7.8	0	0	7.8	0	0
Wires	0.0146	0	0	0	0	-15.78	0	0	-15.78	0
Total	**2.373**							**0.6855**	**-13.8146**	**0.0000**

Table 9: COM Calculation of the Arm Section 3

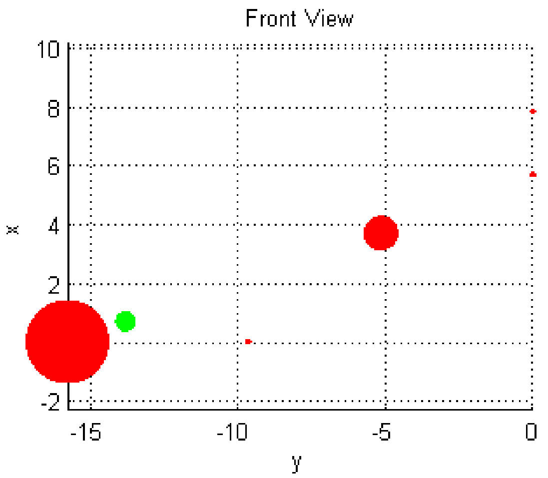


Figure 16: Visualizing the center of mass calculation of the Arm section 3 with a scatter plot in the front view

8 Section 7: Arm Joint 4

The fourth joint of the arm consists of the following parts:

1. Motor M4
2. Connector Bracket C45
3. M4-C45 Screws
4. C45-M5 Screws
5. Cap M4-C45
6. Wires through M4

Figure 17 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 10 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

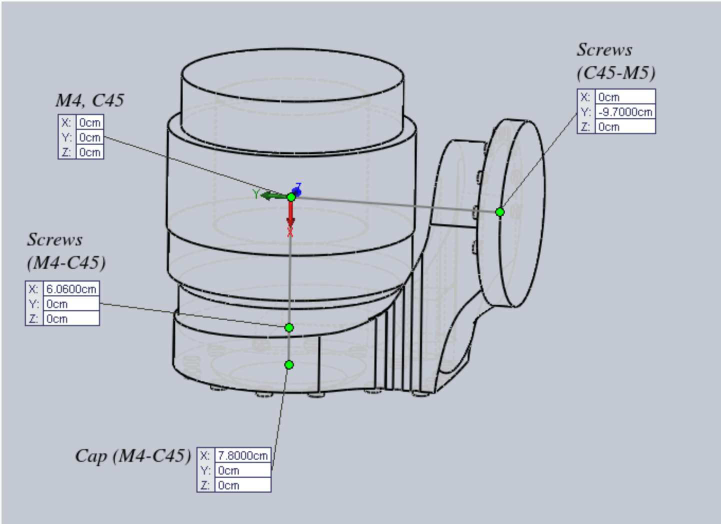


Figure 17: Part origins of Arm Section 4

Part	**Mass**	**Local COM**			**Part origin**			**Section COM**		
		x	**y**	**z**	**x**	**y**	**z**	**x**	**y**	**z**
M4	1.938	0	0	0	0	0	0	0	0	0
C45	0.359	4.26	-4.35	0	0	0	0	4.26	-4.35	0
M4-C45 Screws	0.0192	0	0	0	6.06	0	0	6.06	0	0
C45-M5 Screws	0.0192	0	0	0	0	-9.7	0	0	-9.7	0
Cap	0.023	0	0	0	7.8	0	0	7.8	0	0
Wires	0.0146	0	0	0	0	0	0	0	0	0
Total	**2.373**							**0.7691**	**-0.7366**	**0.0000**

Table 10: COM Calculation of the Arm Section 4

In order to visually verify the calculation of the center of mass in table 10 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 18. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

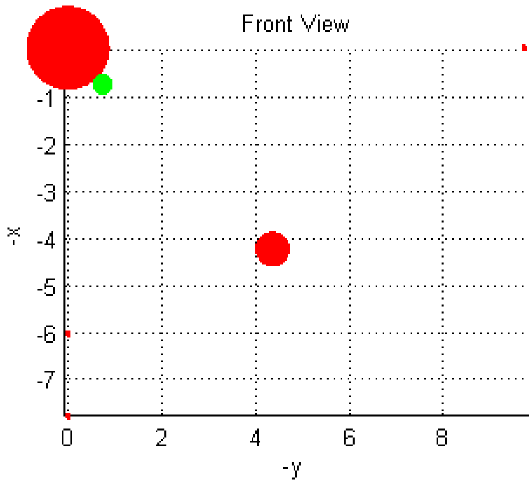


Figure 18: Visualizing the center of mass calculation of the Arm section 4 with a scatter plot in the front view

9 Section 8: Arm Joint 5

The fifth joint of the arm consists of the following parts:

1. Motor M5
2. Connector Bracket C56
3. M5-C56 Screws
4. C56-M6 Screws
5. Cap C56-M6
6. Wires through M5

Figure 19 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 11 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

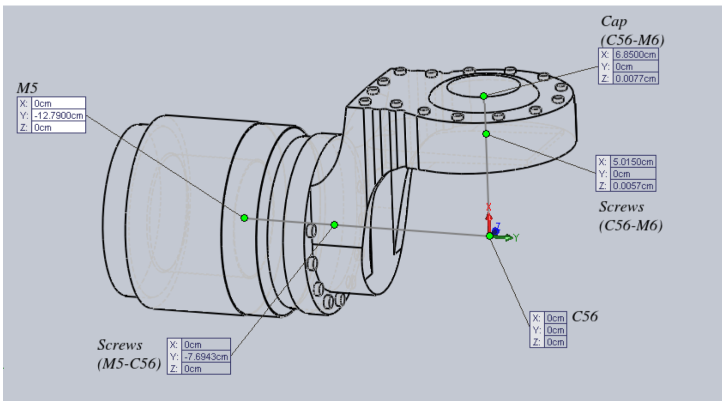


Figure 19: Part origins of Arm Section 5

In order to visually verify the calculation of the center of mass in table 11 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 20. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

Part	Mass	Local COM x	y	z	Part origin x	y	z	Section COM x	y	z
M5	1.118	0	0	0	0	-12.79	0	0	-12.79	0
C56	0.253	3.25	-3.96	0	0	0	0	3.25	-3.96	0
M5-C56 Screws	0.00792	0	0	0	0	-7.6943	0	0	-7.6943	0
C56-M6 Screws	0.00792	0	0	0	5.015	0	0	5.015	0	0
Cap	0.014	0	0	0	6.85	0	0	6.85	0	0
Wires	0.0125	0	0	0	0	-12.79	0	0	-12.79	0
Total	**1.41334**							**0.6777**	**-10.9824**	**0.0000**

Table 11: COM Calculation of the Arm Section 5

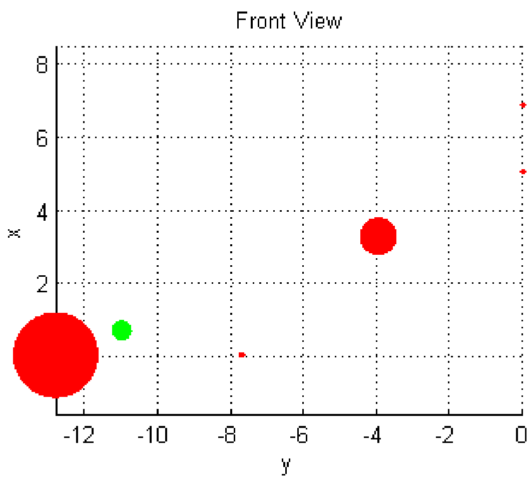


Figure 20: Visualizing the center of mass calculation of the Arm section 5 with a scatter plot in the front view

10 Section 9: Arm Joint 6

The sixth joint of the arm consists of the following parts:

1. Motor M6
2. Motor M7 + FT sensor
3. Connector Bracket C67
4. FT Cap
5. FT Extension
6. NetcanFT Card
7. M6-C67 Screws
8. C67-M7 Screws
9. FT Screws
10. Wires through M6

Figure 21 shows the section frame of reference and the part origins for the above mentioned parts. Note that wires are not mentioned in the figure. We assume the center of mass of the wire to be the same as that of the motor through which they are passing in all arm sections. The mass measurements of each part and the local COMs are discussed in the appendix. Table 12 lists the masses, local COMs and calculates the COM of the section using equation 1. The last row of the table shows the COM of the section.

In order to visually verify the calculation of the center of mass in table 12 we plot a scatter-plot of the section COMs of the parts with a red marker of size proportional to the mass of the part. This is shown in figure 22. The figure shows the scatter plot in just the front view as the z-dimension is irrelevant. The green marker shows the center of mass of the entire section. The size of this marker is arbitrary. From this plot we can visually verify that the calculation was correct.

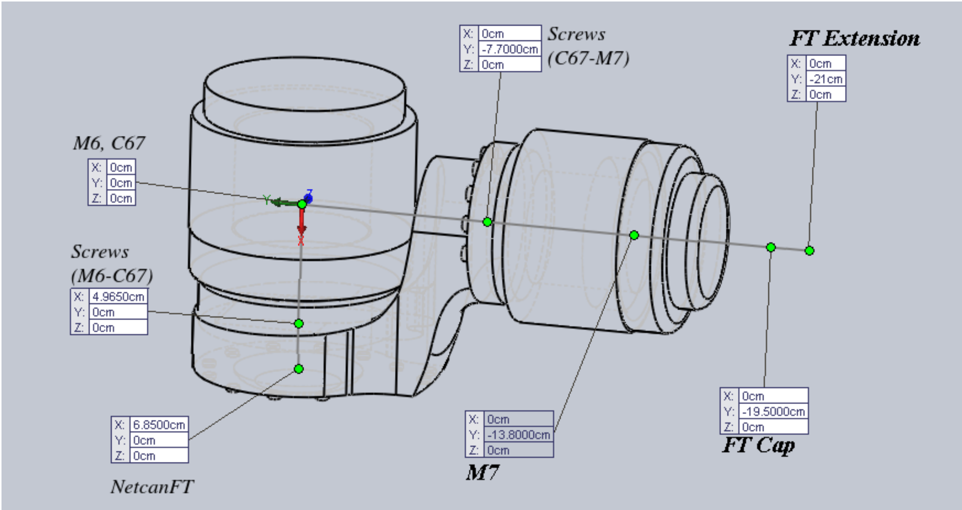


Figure 21: Part origins of Arm Section 6

Part	**Mass**	**Local COM** x	y	z	**Part origin** x	y	z	**Section COM** x	y	z
M6	1.116	0	0	0	0	0	0	0	0	0
C67	0.222	3.79	-3.15	0	0	0	0	3.79	-3.15	0
M6-C67 Screws	0.00792	0	0	0	4.965	0	0	4.965	0	0
C67-M7 Screws	0.00792	0	0	0	0	-7.7	0	0	-7.7	0
NetcanFT	0.091	0	0	0	6.85	0	0	6.85	0	0
Wires (M6)	0.0125	0	0	0	0	0	0	0	0	0
M7 + FT Sensor	0.955	0	0	0	0	-13.8	0	0	-13.8	0
FT Cap	0.033	0	0	0	0	-19.5	0	0	-19.5	0
FT Extension	0.169	0	0	0	0	-21	0	0	-21	0
FT Screws	0.032	0	0	0	0	-19.5	0	0	-19.5	0
Wires (M7)	0.0108	0	0	0	0	-13.8	0	0	-13.8	0
Total	**2.64634**							**0.5684**	**-7.1438**	**0.0000**

Table 12: COM Calculation of the Arm Section 6

11 Validation of Total Arm Mass

As a verification of the analysis done on the arm sections we compare the sum total of all arm sections with the mass of the full arm measured. Figure 23A shows that the total mass of left arm is $16.58kg$ and figure 23B shows that total mass of the right arm is $16.62kg$. Table 13 shows the total estimated mass of the arm calculated by adding up the masses of the individual sections of the arm is $16.6827kg$.

Arm Section	Total Mass (kg)
Arm section 1	3.952
Arm section 2	3.925
Arm section 3	2.373
Arm section 4	2.373
Arm section 5	1.4133
Arm section 6	2.6463
Total	16.6827

Table 13: Total estimated mass of the arm

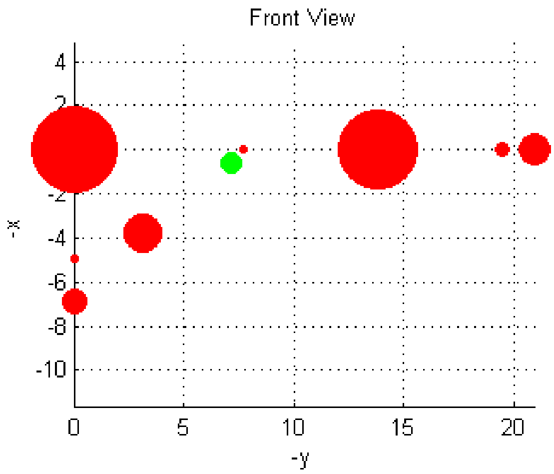


Figure 22: Visualizing the center of mass calculation of the Arm section 6 with a scatter plot in the front view

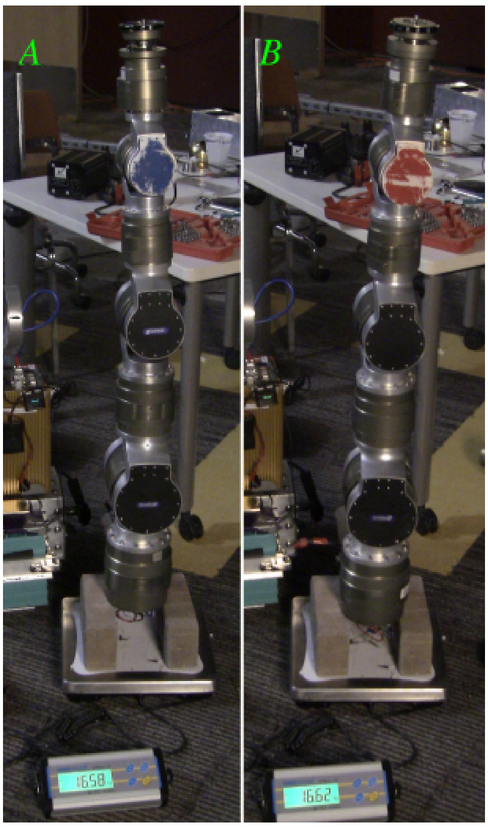


Figure 23: Total mass of A. Left Arm B. Right Arm

12 Section 10: End-effector

The last section of the arm that rotates with the rotation of Motor 7 is the end-effector. The coordinate system chosen for the section frame of reference in this case is the same as was defined in the data sheet of the Robotiq end-effector. The same data sheet provides the center of mass of the end-effector (figure 24). As the end-effector is the only part of the section, there is no need for any calculation. The center of mass of the this section is therefore $(x, y, z)_{COM} = (-0.8, 0.0, 6.5)cm$. The mass of the gripper is $2.3kg$ according to the datasheet.

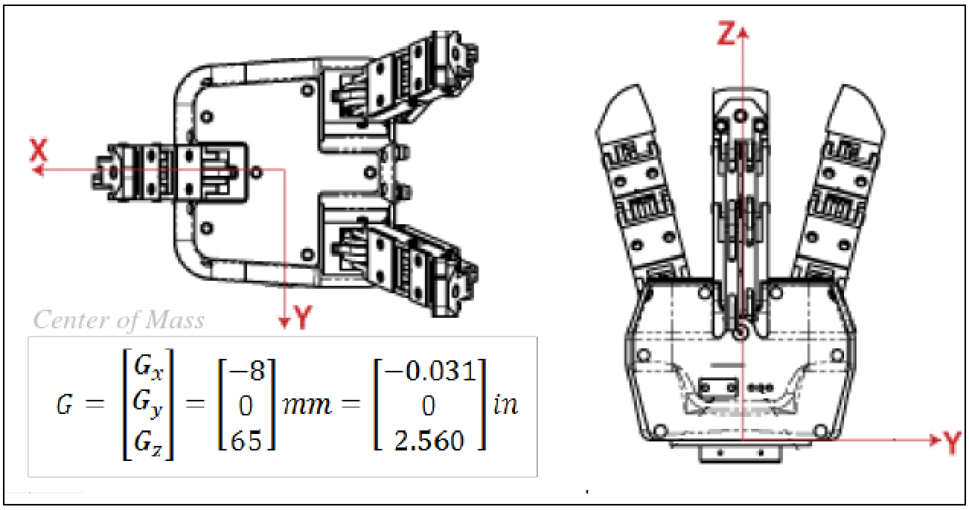


Figure 24: COM of the end-effector taken from its datasheet

13 Section 4B: Kinect

Apart from the two arms there is a third branch that is attached with the shoulder bracket (i.e. section 3). This is the kinect. Kinect is mounted on the part we named kinect holder in bracket section using two hinges with no actuation. Section frame of reference is defined to be at the axes of rotation about the hinges at the midpoint between the two hinges. This section consists only of one part i.e. kinect. Its mass is measured to be $0.705kg$. The geometrical center of kinect is assumed to be the center of mass of the section. As visualized in figure 25, the center of mass is $(x, y, z)_{COM} = (0.0, -4.0, -2.8)cm$.

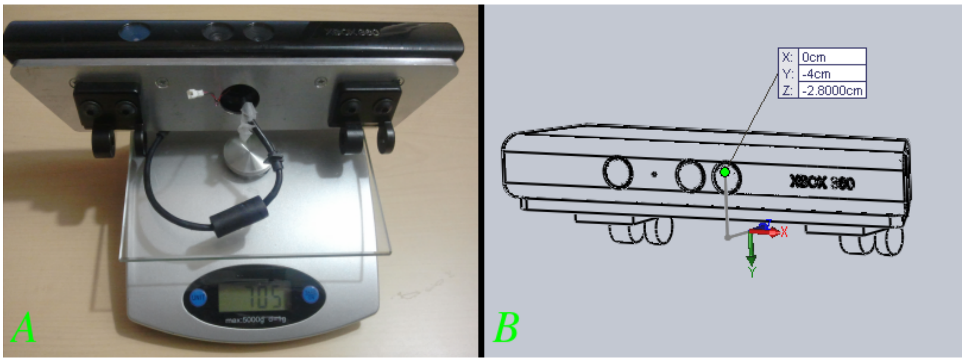


Figure 25: A. Mass measurement and B. center of mass visualization of the kinect section

14 Full-body COM

The COM of the full robot is calculated using equation

$$X_{full}(q) = \frac{\sum m_j X_j^w(q)}{\sum m_j} \tag{4}$$

where $X_{full}(q)$ is the COM of the full robot expressed in world frame and is a function of the current pose q of the robot, m_j is the mass of jth section and $X_j^w(q)$ is the COM of the jth section expressed in world frame also a function of the current pose q of the robot. The COMs of the sections calculated in the preceding sections were expressed in the respective section frame of reference. To express this COM in the world frame of reference it needs to be transformed using the section transformation matrix calculated using the current pose (and forward kinematics) of the robot to transform section frame into the world frame.

$$X_j^w(q) = T_j^w(q)X_j^j \tag{5}$$

where $T_j^w(q)$ is the section transformation matrix calculated using the current pose q of the robot. q represents the joint positions of the individual joints of the robot. X_j^j is the COM of the individual section expressed in the local frame of reference, and is calculated and presented in the earlier sections of the report.

Let O be the midpoint of the line segment connecting the two wheel centers and X be the full body COM. The *balancing angle* θ is defined as the angle between line OX and the vertical. Once we have the the full COM of the robot $X_{full}^w(q) = (x, y, z)_{full}$, we can find θ using

$$\theta = arctan(\frac{x}{z}) \tag{6}$$

Notice that if the current pose of the robot is such that the COM lies right above the wheel-axis, then the x-component of the COM will be zero making $\theta = 0$.

15 Validation

We calculated the COM of the full robot based on equations (4-5) in specific poses of the robot using the section COMs presented in the earlier sections. In order to validate this COM we compared it against two quatities that could be physically measured: 1. The balancing angle 2. The x-component of the COM.

For the balancing angle, we make the robot balance itself, in which case, the COM will be right above the wheel-axis, so $\theta = 0$. At this point the balancing angle calculated using equation(6) should also be zero. A non-zero value will reflect the error in the estimation of the COM. We made this comparison for ten different poses of the robot (3 different waist angles with 3 different hand positions, plus an extra hand position for the last waist-angle case).

For the x-component of the robot we placed both wheels of the robot on weight scales and made it rest on its caster. The x-component of the full robot's COM can now be calculated using $x = \frac{m_1x_1+m_2x_2}{m_1+m_2}$ where m_1 is the total weight sensed by the two scales, $x_1 = 0$ is the x-coordinate of the wheel axis in the world frame, $m_2 = m_{full} - m_1$ is the weight that would be sensed if a scale was placed below the caster and x_2 is coordinate of the point on the caster at which the robot is made to rest, measured out to be $37.5cm$. $m_{full} = 144.5kg$ is the full weight of the robot calculated by summing the wiights of the individual sections presented earlier. In the cases where the x_{COM} was greater in magnitude than x_2 i.e. the COM is further behind the caster, the robot could fall over about the caster. To prevent this, we placed some extra weight m_3 on the base using one ($13.32kg$) or two ($13.32 + 13.26kg$) cinder blocks, at $x_3 = 3cm$. So the new weight reflected by the two scales m_1^* is now different than m_1 i.e. what would be when there is no m_3. Using torque equation about the caster, we can calculate $m_1 = m_1^* - m_3\frac{|x_2|+|x_3|}{|x_2|}$.

Figure 26 shows the ten different poses of the robot where we took the aforementioned measurements. In cases 1A, 1B, 1C, ... 3D, the numbers 1, 2 and 3 represent three cases of waist angles (closed, half-open, wide-open). And the cases A, B, C, D represent the different poses of the two arms (forward, one-straight-side-one-straight-up, both-twisted-behind, both-forward-down). These cases try to capture representative samples from the entire pose space. For each of the ten cases the four figures a, b, c and d represent a) the measurement of COM and balancing angle while balancing b) the measurment of the COM and balancing angle while resting on the caster c) A front view of the actual robot when taking measurement while it's resting on the caster d) The values read on the two weight scales on which the wheels are resting. Note that cinder blocks are placed on the base in cases 3A, 3B and 3C. Table 14 shows the results of the eperiments. The last two columns represent the error. We see that the errors are very close to zero in all cases.

Figure 26: Measuring the COM and balancing angles in ten different robot poses in order to verify the full-body COM calculation

Pose	**Scale 1**	**Scale 2**	m_1	m_2	**Measured** x_{COM}	**Estimated** x_{COM}	**Error in** x_{COM}	**Error in** θ
1A	72.60	70.40	143.00	1.50	-0.39	-0.57	0.18	0.04
1B	65.18	74.88	140.06	4.44	-1.15	-1.02	-0.13	-0.37
1C	58.40	55.70	114.10	30.40	-7.89	-6.67	-1.21	-0.69
2A	17.34	16.92	34.26	110.24	-28.61	-27.99	-0.62	0.43
2B	5.54	22.42	27.96	116.54	-30.24	-29.25	-1.00	0.56
2C	11.74	13.08	24.82	119.68	-31.06	-30.68	-0.38	-0.07
3A	13.34	15.44	-0.28	144.78	-37.57	-37.72	0.15	0.46
3B	3.38	20.90	-3.72	148.22	-38.46	-37.82	-0.65	0.58
3C	5.68	5.96	-2.39	146.89	-38.12	-37.23	-0.89	0.19
3D	15.18	15.24	30.42	114.08	-29.61	-29.40	-0.21	0.49

Table 14: Error estimation in full-body COM

16 Appendix A

This section contains the figures used as the basis to estimate the masses and center of masses of the parts mentioned in the report.

16.1 Core Base

Raw Data and Setup

The core is defined to include the chassis, the blue box, the PSU and the cables. Figure 27 demonstrates four sides around the base and the top which shows the cables. Total mass is $29.72 + 16.96 = 46.68$ kg.

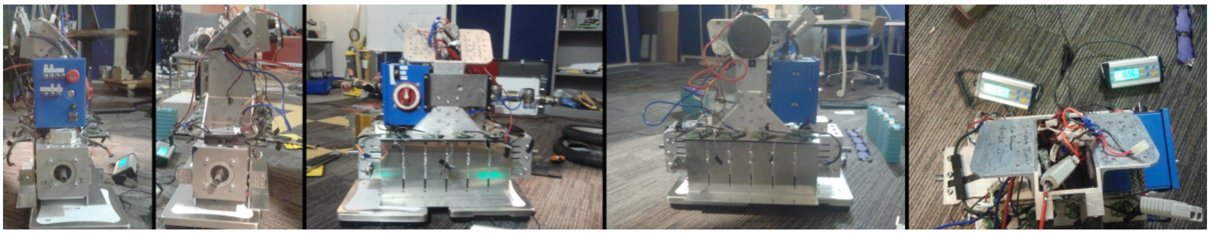


Figure 27: The setup before measurements

In Figure 28, the center of mass measurements for each dimension and where the poles are placed at each trial is shown. For the dimension between the wheels, we place the poles under the screws. For the second dimension between the front and back of the chassis, the poles are placed at the first and second thirds of the battery holders. For the third dimension, a brick is placed under the battery holder and a pole is placed under the caster such that the chassis is horizontal.

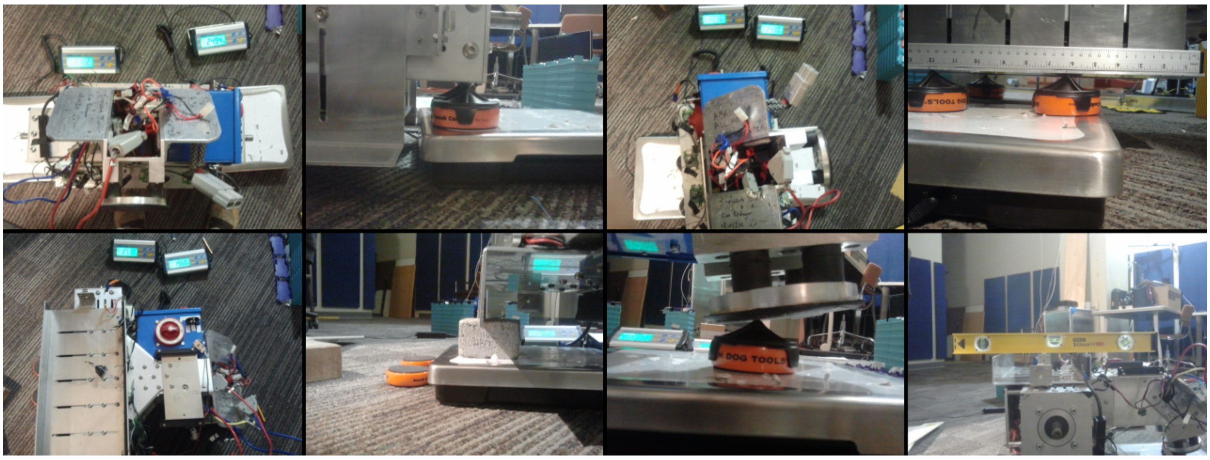


Figure 28: The measurements about three axes with the placements for the poles

Local center of mass

The coordinates of the points of contacts that were used to measure the masses in figure 28 are shown in figure 29. These coordinates are measured with respect to the frame of reference located at the part origin.

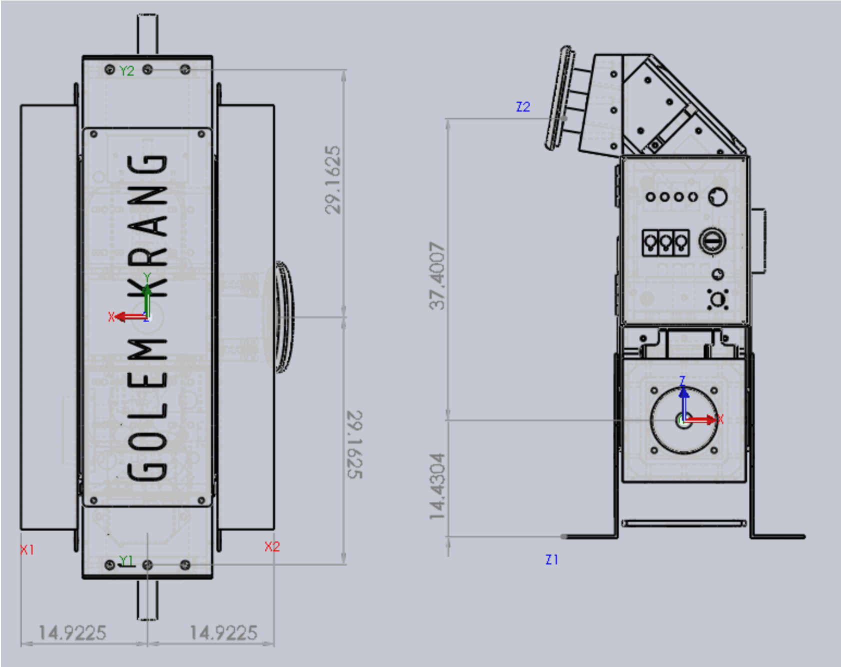


Figure 29: The dimensions between the poles necessary to compute the center of masses

Table 15 shows the computation of the center of mass of the core based on the measurements shown in figures 28 and 29.

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}(cm)$
x	22.36	24.30	14.9225	-14.9225	-0.6204
y	24.94	21.82	-29.1625	29.1625	-1.9458
z	27.10	19.60	-14.4304	37.4007	7.3231

Table 15: Base Core COM

The computed center of mass is shown in the figure 30.

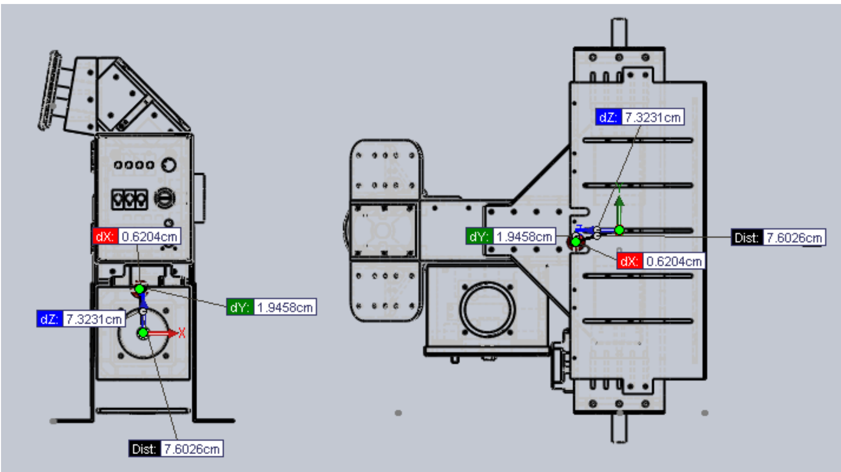


Figure 30: The dimensions between the poles necessary to compute the center of masses

16.2 Battery sets

Raw Data and Setup

A battery set contains four batteries, four caps (purple) and the screws that hold the electronic boards to the batteries. Figure 31 shows the weight measurements for the front and back sets, the center of mass data for a single battery and the weight of the screws on both sides. Note that we assume that the center of mass at shorter dimensions are in the middle, and we are only interested in the longer one. The mass for a battery set is 8.52 or 8.54 kg based on the side and the total with the screws is 8.536 or 8.556 kg. So the mass of a single battery is taken from these measurements as $8.536/4 = 2.134$ kg for the front batteries and $8.556/4 = 2.139$ kg for the rear batteries.

For the center of mass measurement, the poles are placed at the corners of the battery and the readings are 0.90 and 1.22 kgs. In the next section, we will compute the center of mass of the battery set using the single battery and the weight of the screws. We make an assumption that all batteries have the same center of mass locations.

Figure 31: The mass readings for the battery sets, the screws, and the center of mass reading for a battery

Local center of mass

The z-coordinates of the pole locations used to measure the center of mass of the battery are shown in figure 32 (left). Using $m_1 = 0.916kg$, $m_2 = 1.22kg$, $z_1 = 10.15cm$, $z_2 = -10.15cm$ and $z_{COM} = \frac{m_1 z_1 + m_2 z_2}{m_1 + m_2} = -1.4446cm$, where we include the mass of the screws in m_1 measurement. This COM is shown in figure 32 (right).

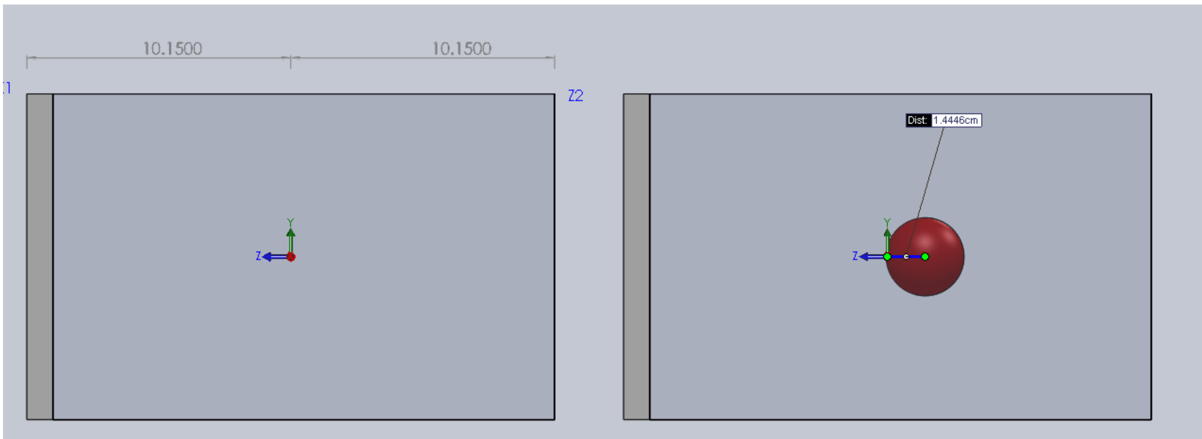


Figure 32: The length of the battery and the visualization of the center of mass

The center of mass of the battery is therefore $(x, y, z)_{COM} = (0.0, 0.0, -1.4446)cm$.

16.3 Main Computer

Raw Data and Setup

Figure 33 shows the raw measurements for the main computer taken using two scales along each of the three dimensions, along with the mass measurement of the screws (screws for vision computer are included) which is $0.023kg$ and that of the wifi cable $0.16kg$. The total mass of the computer is taken from the top-right image as it does not contain the masses of the small accessories mounted on the computer. It is $3.04 + 3.30 = 6.34kg$.

For the center of mass measurements the poles are placed at the edges of the computer.

Figure 33: Mass and center of mass readings for main computer, the screws and the wifi cables attached

Local Center of Mass

Figure 34 shows the distances between the points of contact that were used to measure the center of masses along each of the three dimensions. The following table shows the results of computation for center of mass. Note the coordinate system according to which all coordinates have been calculated:

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
x	3.30	3.04	0	15.43	7.3986
y	3.32	3.04	0	22.574	10.79
z	3.30	3.08	0	23.78	11.48

Table 16: Main Computer COM

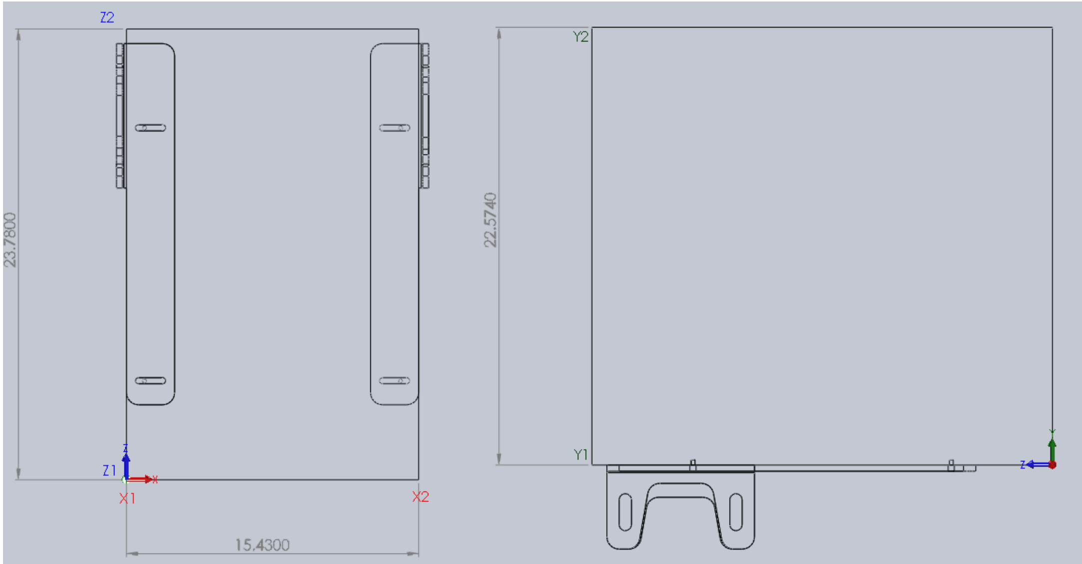


Figure 34: The dimensions between the poles necessary to compute the center of masses

The resulting center of mass is thus $(x, y, z)_{COM} = (7.3986, 10.79, 11.48)cm$ in the part coordinate system. This is shown in figure 35.

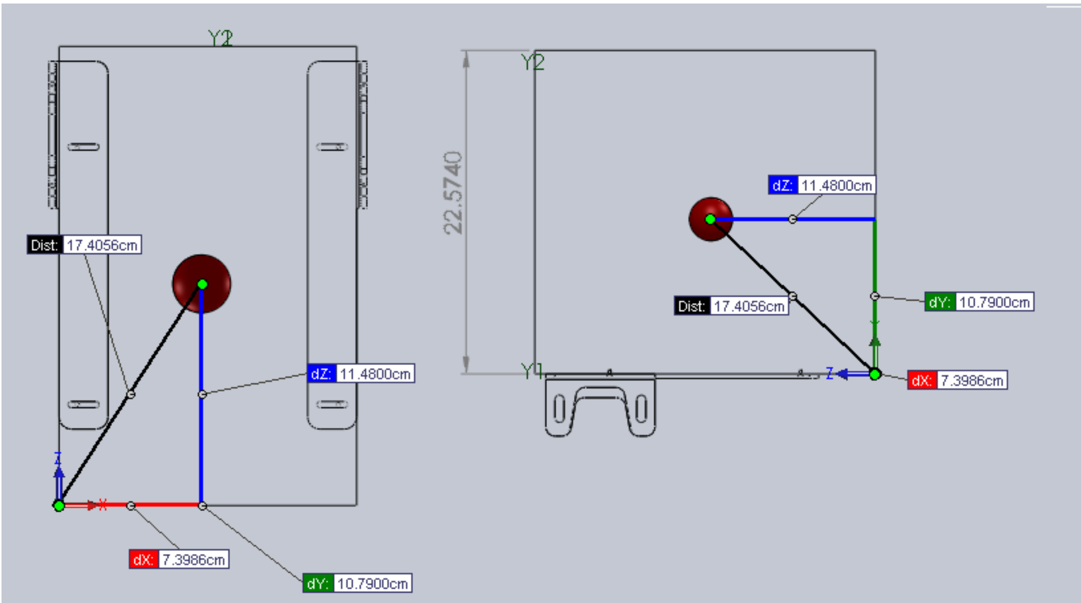


Figure 35: The estimated center of mass of the main computer on the base

16.4 Vision Computer

Raw Data and Setup

Figure 36 shows the raw measurements for the vision computer taken using two scales along two dimensions. The total mass of the vision computer is $0.80 + 0.84 = 1.64kg$.

For the center of mass measurements the poles are placed at the edges of the plane section of the computer.

Figure 36: Mass and center of mass readings for vision computer

Local Center of Mass

Figure 37 (left) shows the coordinates of the points of contact that were used to measure the center of masses along each of the two dimensions. The following table shows the results of computation for center of mass. Note the coordinate system according to which all coordinates have been calculated is chosen to be at the center of the vision computer. Along the x-axis the center of mass is supposed to be at the mid-point (i.e. x-coordinate of the COM is zero).

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
y	0.88	0.76	-9.5	9.5	-0.6951
z	0.80	0.84	10.75	-9.15	0.5573

Table 17: Vision Computer COM

The resulting center of mass is thus $(x, y, z)_{COM} = (0.0, -0.6951, 0.5573)cm$ in the part coordinate system. This is shown in figure 37 (right).

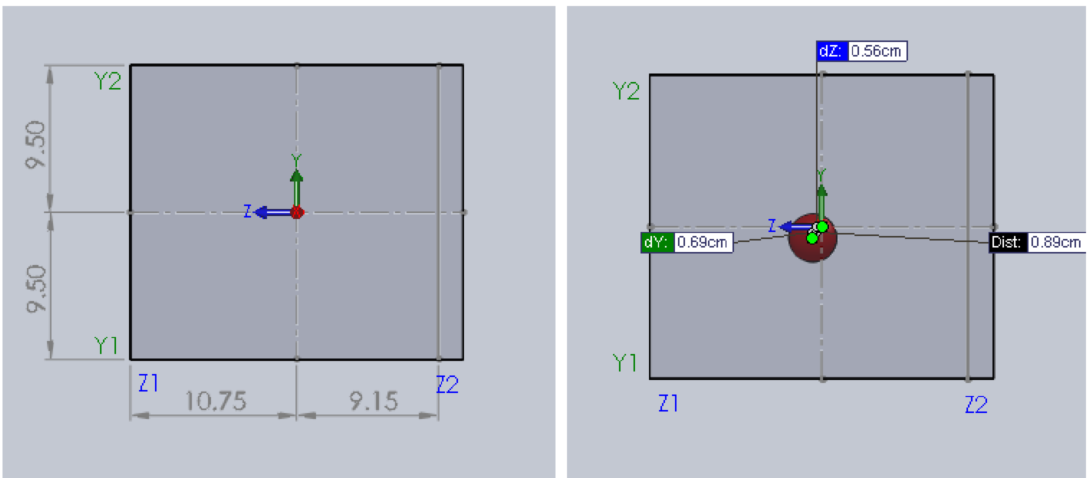


Figure 37: The coordinates of the points of contact used to measure the center of masses (left) and visualization of the estimated center of mass of the vision computer on the base (right)

16.5 Waist plate

Figure 38A shows the measured mass of the waist plate is $1.08kg$. Since the part's geometry is easily modeled and the density is assumed uniform, SolidWorks is used to determine the center of mass of the waist plate, shown in figure 38B. It turns out to be $(x, y, z)_{COM} = (-5.54, 0.0, 6.16)cm$. This is visualized in figure 38C.

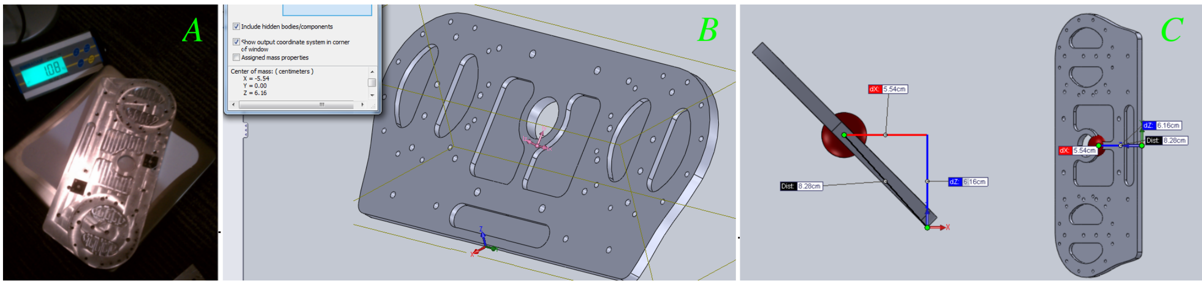


Figure 38: A. Mass reading for the waist plate B. Center of Mass of the waist plate as determined by SolidWorks C. COM Visualization of the Waist Plate

16.6 Waist brackets

Figure 39 shows the mass measurement of the waist brackets. The left waist bracket measures $0.473kg$ and the right waist bracket measures $0.480kg$.

Figure 39: Mass reading for the waist brackets

The coordinate system in which we express the center of mass of the brackets is chosen differently for the right and the left bracket and is shown in figure 40. The origin of this frame of reference is the center of the bottom circular face of the brackets and the axes are such that they are aligned with the base section frame of references (which is true for all parts of any specific section). This would mean that the center of mass of the right frame will have same x and z components but the y-component would be equal and opposite.

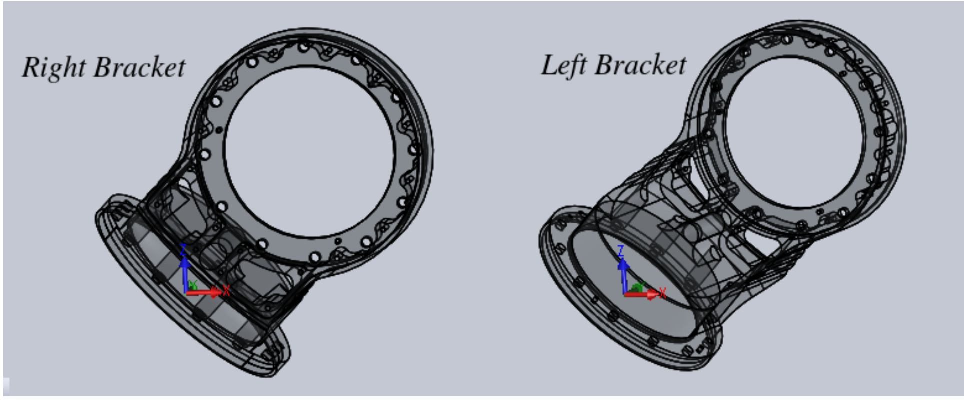


Figure 40: The part frames of references of the left and right waist brackets

Since the geometry of the part is easily modeled and the density assumed uniform, we use Solidworks to determine the center of mass of the brackets. Figure 41 shows that the center of mass for the left bracket is $(x, y, z)_{COM}|_{wbL} = (3.98, 4.93, 3.98)cm$. For the right bracket, therefore, the coordinates will be $(x, y, z)_{COM}|_{wbR} = (3.98, -4.93, 3.98)cm$.

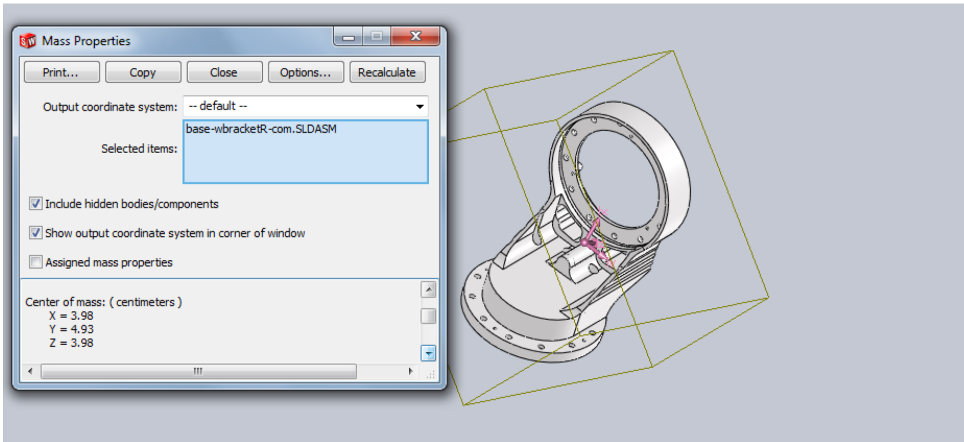


Figure 41: Center of Mass of the waist bracket on the left side as determined by SolidWorks

The center of mass of the waist bracket is visualized in figure 42.

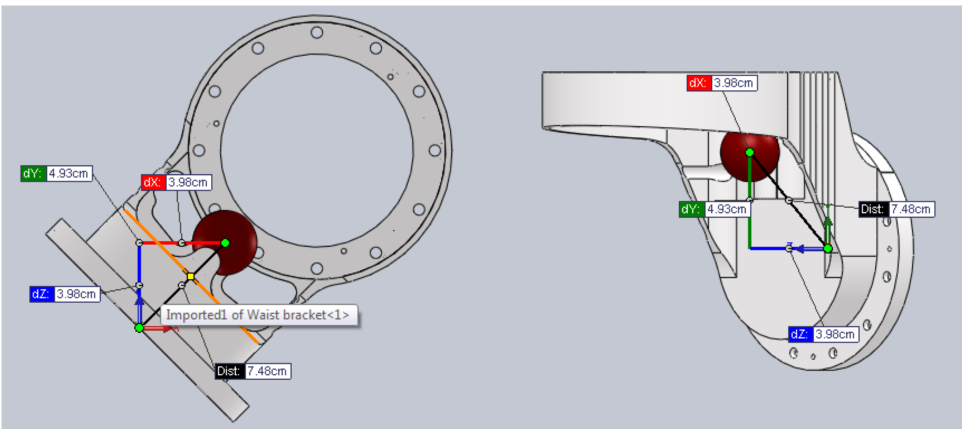


Figure 42: Center of Mass Visualization of the Waist bracket on the left side

16.7 Small Parts: Battery Mats, Battery Straps, Waist Spacers, Waist Bracket Screws and Waist Plate Screws

Figure 43 shows the mass measurements of the some of the smaller parts in the base. For all these parts we use their symmetry to locate the center of masses in the geometric center of the parts. So the part center of mass in each of the case will be $(0.0, 0.0, 0.0)cm$. Table 18 shows the masses of each of the parts based on the measurements.

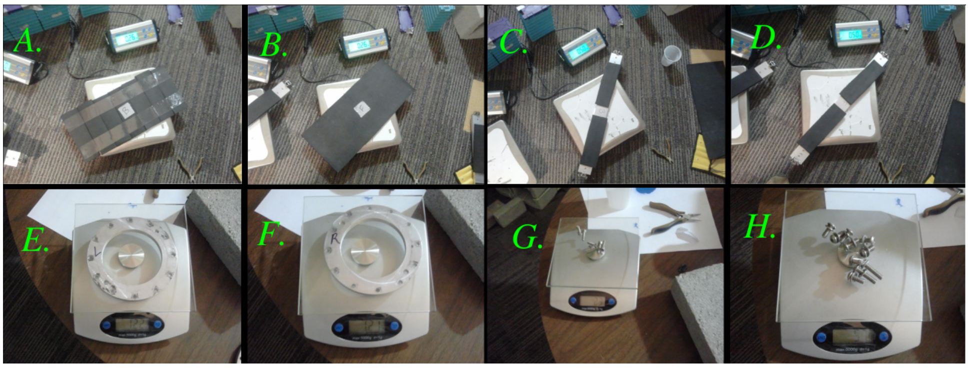


Figure 43: Masses measurements of the smaller parts in the base section: A. Battery mat on the rear B. Battery mat on the front C. Battery strap on the rear D. Battery strap on the front E. Waist Spacer on the Left F. Waist Spacer on the right G. Waist Bracket Screws (6) H. Waist plate screws (all)

Part	Mass (kg)
Battery Mat (Rear)	0.26
Battery Mat (Front)	0.26
Battery Strap (Rear)	0.50
Battery Strap (Front)	0.50
Waist Spacer (Left)	0.122
Waist Spacer (Right)	0.121
Waist Bracket Screws (Left)	0.046
Waist Bracket Screws (Right)	0.046
Waist Plate Screws	0.05

Table 18: Mass measurements of the small parts in the base section

16.8 Spine Tube

The tube is a metallic four-sided hollow prism that forms the actual spine of the robot. Figure 44A shows the raw mass measurement of the tube. Notice there is a red colored device mounted on the tube. This is a ring bolted on the spine to allow a safety mechanism (maybe a gantry) to hook on it and hold the robot from falling. The measured mass is $3.453kg$.

Since the geometry of the part is easily modeled and the density assumed uniform, we use Solidworks to determine the center of mass of the brackets. Figure 44B shows that the center of mass for the tube with respect to the part frame of reference whose origin is chosen to be the bottom-right corner of the tube at the front face. The center of mass estimated by SolidWorks is $(x, y, z)_{COM} = (-4.841, 5.080, 26.216)cm$. This center of mass of the tube is visualized in figure 44C.

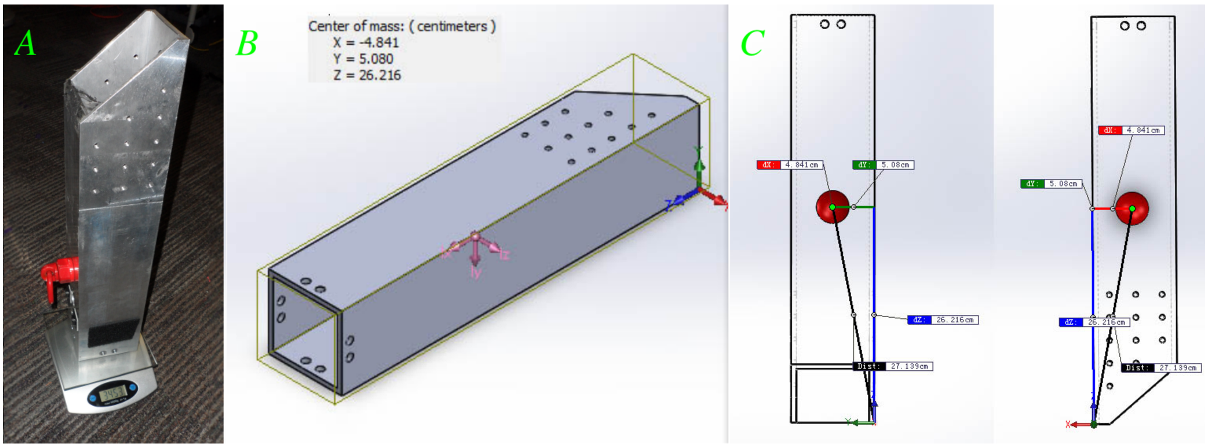


Figure 44: A. Mass reading for the spine tube along with gantry B. COM estimation by solidworks (note: gantyr not included) C. Visualization of the COM of the tube

16.9 Side Plates

Side Plates connect the left and right waist motors to the spine tube. Figure 45 shows the mass measurement of the side plate on the left (indicated by the '14' written on it indicating that module 14 connects to it which is the module number of the left waist motor). The mass measured is $0.513kg$. The plate on the right is assumed to have the same mass.

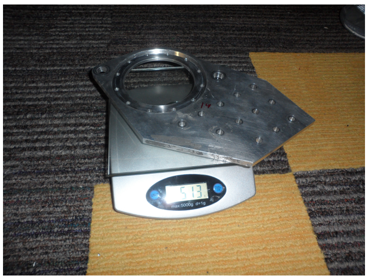


Figure 45: Mass reading for the side plates

The coordinate system in which we express the center of mass of the brackets is chosen differently for the right and the left side plate. The origin of this frame is on the center of the circular cut on the plates lying on the plane co-incident to the face of the side plate that is closer to the center of the robot.

Since the geometry of the part is easily modeled and the density assumed uniform, we use Solidworks to determine the center of mass of the brackets. Figure 46 shows that the center of mass for the left bracket and the right bracket with respect to their respective co-ordinate systems as estimated by SolidWorks is $(x, y, z)_{COM}|_{sidePlateL} = (-7.233, 0.451, 2.479)cm$. For the right bracket, therefore, the coordinates will be $(x, y, z)_{COM}|_{sidePlateR} = (-7.233, -0.451, 2.479)cm$.

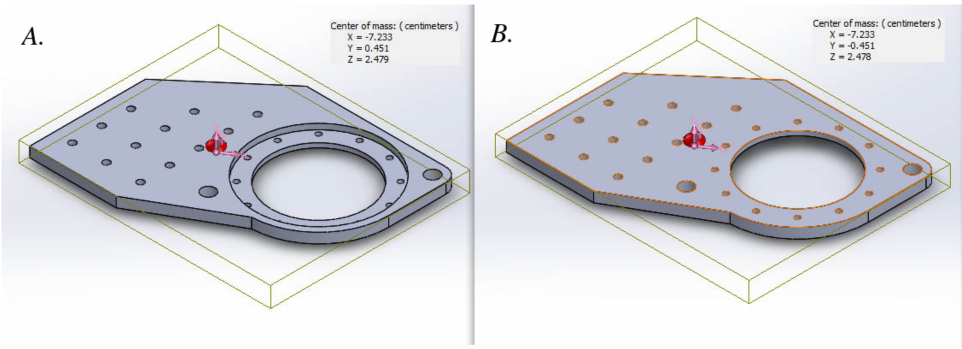


Figure 46: Center of Mass of A. Left Side Plate B. Right Side Plate

The center of mass of the side plates is visualized in figure 47.

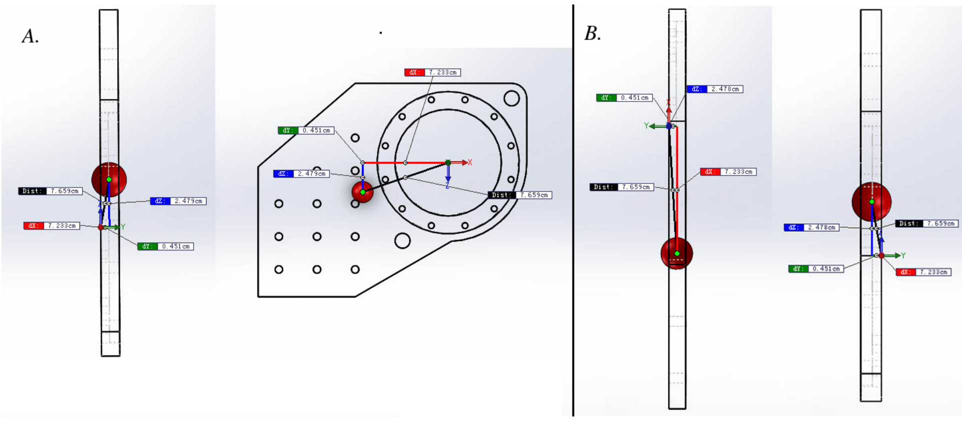


Figure 47: Center of Mass Visualization of the A. Left Side Plate B. Right Side Plate

16.10 Waist Motors

The PRL120 is used for each of the two waist motors. Figure 48 shows the mass measurement of the module, with its interface board mounted on it, used as the left waist motor. This mass turns out to be $3.307kg$.

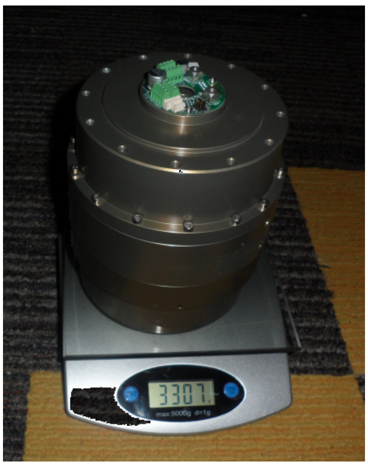


Figure 48: Mass reading for the Waist motor

The coordinate system in which we express the center of mass of the waist motors is chosen differently for the right and the left side plate. The origin of this frame is on axis of the motor lying on the plane co-incident with the surface of the waist module that couples with the respective side plates.

We assume here that the center of mass of the module is at the center of the two side-faces of the module and on the axis of the module i.e. roughly the geometric center of the motor if it is considered as a uniform cylinder. Figure 49 shows that the center of mass for the left motor and the right motor with respect to their respective co-ordinate systems is $(x, y, z)_{COM}|_{waistMotorL} = (0.0, 6.975.0.0)cm$ and $(x, y, z)_{COM}|_{waistMotorR} = (0.0, -6.975, 0.0)cm$.

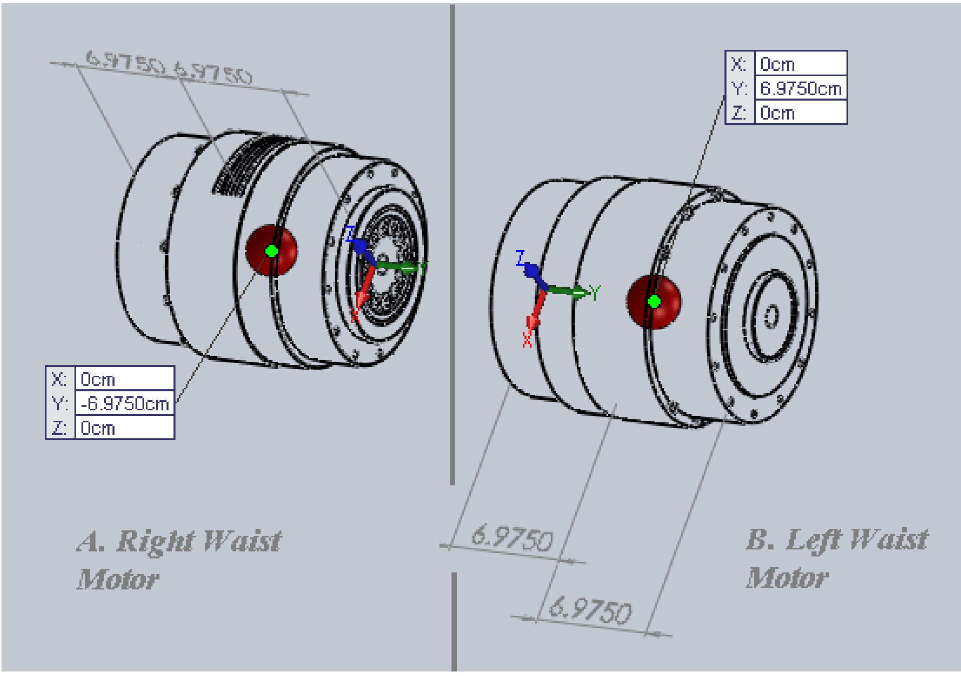


Figure 49: Center of Mass of A. Right Waist Motor B. Left Waist Motor

16.11 End-Cap

On the top of the spine tube there is a rigid mechanical interface to the toros motor which we call end-cap. It is coupled to the spine tube using 8 screws. Figure 50A shows the mass measurement of the end-cap along with th screws. It is $0.76kg$.

The coordinate system in which we express the center of mass is on at the center of the top face of the end-cap. As the geometry is known and the material is uniform, SolidWorks is used to determine the center of mass shown in figur 50B.

The center of mass of end cap is visualized in figure 50C. 47.

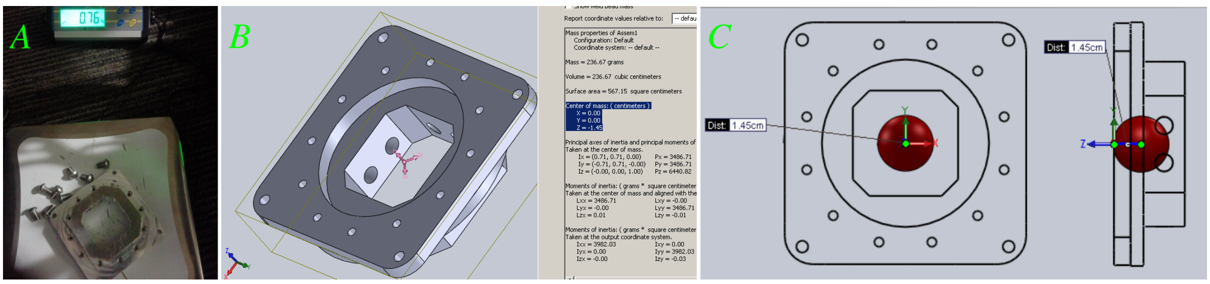


Figure 50: A. Mass reading for end-cap along with screws B. Center of Mass of end-cap as determined by SolidWorks. C. Center of Mass Visualization of the End-Cap

16.12 Spine Small Parts

The small parts in Spine include: 1) Capacitor 2) Rubber rings 3) Bolts assembly 4) Waist Motor Caps 5) Schunk module to bracket screws 6) Schunk module to side plate screws 7) Side Plate Screws. Figure 51 shows the mass measurements of these parts.

Figure 51: Mass measurements: A. Capacitor B. Rubber Rings C. Bolt Assembly Nut D. Bolt Assembly Washer E. Bolt Assembly Screws and Spacer F. Waist Motor Cap G. Waist Bracket Screws H. Waist motor to side plate screws I. Side Plate Screws

part	mass (kg)
Capacitor	0.162
Rubber Rings (x3)	0.029
Bolt Assembly Nut	0.020
Bolt Assembly Washer	0.002
Bolt Assembly Screw and Spacer	0.242
Waist Motor Cap	0.028
Waist Bracket Screws	0.073
Waist motor to side plate screws	0.083
Side Plate Screws	0.108

Table 19: Mass measurements of the small parts in the spine section

16.13 Spine Wires

16.13.1 Raw Data

Spine wires carry all the interconnections between various sections of the robot. Figure 52 shows the raw measurements of all the wires in the spine section. There are a few things to note here:

- Figure 52A shows mass of wire set 1, $0.570kg$ which includes: All logic Power, Waist/Torso Data, Waist/Torso Motor Power, Torso interface board and the empty box shown in figure 52B with mass $0.136kg$. Mass of wire set 1 would therefore be $0.570kg - 0.136kg = 0.434kg$.
- Figure 52C shows measurement of wire set 2, $1.694kg$ and it includes: Arm data cables (without the DB9 ends at the top end), Arm motor power (without power connectors at the bottom end), Speaker USB Cable, Waist Plate which is $1.08kg$ (see Waist Plate section) and the empty box ($0.136kg$ already mentioned). The mass of wire set 2 would therefore be $1.694kg - 1.08kg - 0.136kg = 0.478kg$.
- Figure 52D shows the mass ($0.038kg$) of a sample USB cable 53.5% of the length of the actual kinect USB cable in the spine, so the actual mass would be $0.038kg/0.535 = 0.071kg$.
- Figure 52 E, F show the Kinect USB and power cables
- Figure 52 G, I and J show respectively the RC connector ends for the kinect power, white shield on the arm cables and DB9 ends of the arm data cable missing from the above measurements.

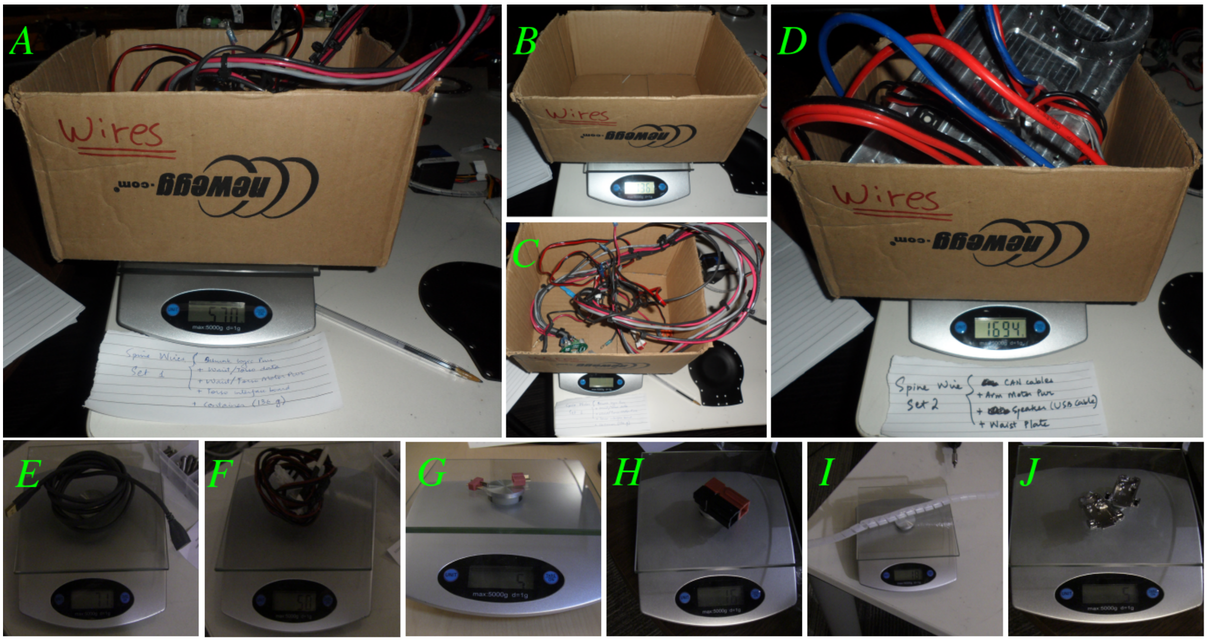


Figure 52: Mass measurements: A. Wire Set 1 B. Empty box used for taking measurements of wire sets 1 ansd 2 C. Wire Set 1 top view D. Wire Set 2 E. USB Cable for kinect data F. Power Cable for kinect G. RC connectors for kinect power cable H. Power Connectors (1 of 3) I. White shield on arm cables J. DB9 ends of arm data cable

Wires	Mass (kg)
Wire Set 1	0.434
Wire Set 2	0.478
Kinect USB Cable	0.071
Kinect Power Cable	0.050
Kinect Power RC Connector	0.005
Motor Power Connectors	0.048
White Shield	0.018
DB9 Ends of Arm data cable	0.01
Total	1.114

Table 20: Mass measurements of the wires in the spine section

16.13.2 Local COM

Since the wires are flexible, assigning values to the center of mass of the wires has to arbitrary. We have chosen the values based on the center of mass calculated of the entire spine section. The value that allows us to best match the estimated center of mass and the one measured of the entire section is $(x, y, z)_C OM = (-14.3664, 0.6479, 7.1952)cm$.

16.14 Torso Motor

PRL120 is used as the torso motor module. Figure 53 shows the experimental setup and measurements of the torso motor. The total mass is $3.26kg$ (fig 53A). The rest of the images are showing the mass measurements taken along three different dimensions. Along the y-dimension (i.e. along the length of the motor) the weight measurements include the weights of the bricks as well which is shown in $2.62kg$ (fig 53B). The two measurements are $4.46kg$ and $4.08kg$ (fig 53C,D). From this masses of the torso motor will be obtained by subtracting the mass of bricks i.e. these readings will be $1.84kg$ and $1.46kg$.

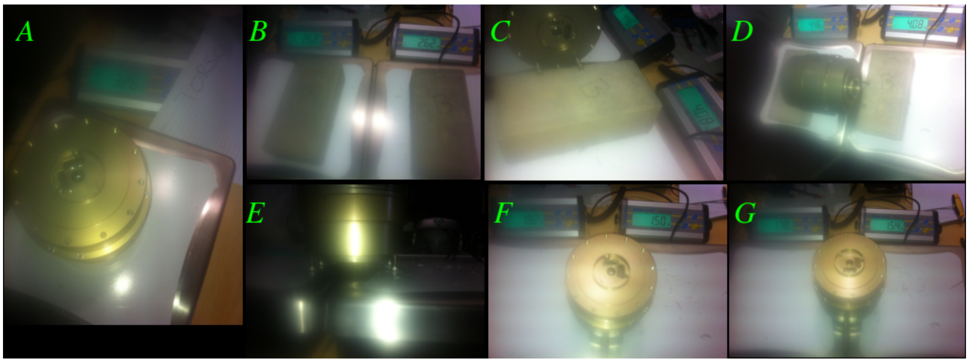


Figure 53: Mass measurements: A. Torso Motor B. Bricks used as platform for torso mass measurement along y-dimension C. D. Torso measurements along y-dimension E. Torso experimental setup for measurements along x-axis F. Torso measurements x-axis G. Torso measurements along z-axis

Figure 54 shows the distances of the measurements shown in figure 53. Note that the screws used at the ends of torso are assumed to be 2 cm away from the surface of torso. The origin is assumed to be at the mid-point between the line connecting the centers of the two end-faces of the torso.

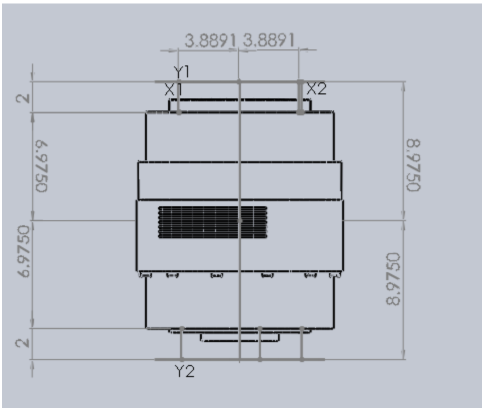


Figure 54: Torso Motor experimental setup distances

Based on the aforementioned distances and masses table 21 deduces the center of mass of the torso motor.

dim	$m_1(kg)$	$m_2(kg)$	$x_1(cm)$	$x_2(cm)$	$x_{COM} = \frac{m_1x_1+m_2x_2}{m_1+m_2}(cm)$
x	1.82	1.5	-3.8891	3.8891	-0.3748
y	1.84	1.46	8.975	-8.975	1.0335
z	1.78	1.54	-3.8891	3.8891	-0.2811

Table 21: Torso COM

The center of mass thus turns out to be $(x, y, z)_{COM} = (-0.3748, 1.0335, -0.2811)cm$. This is visualized in figure 55

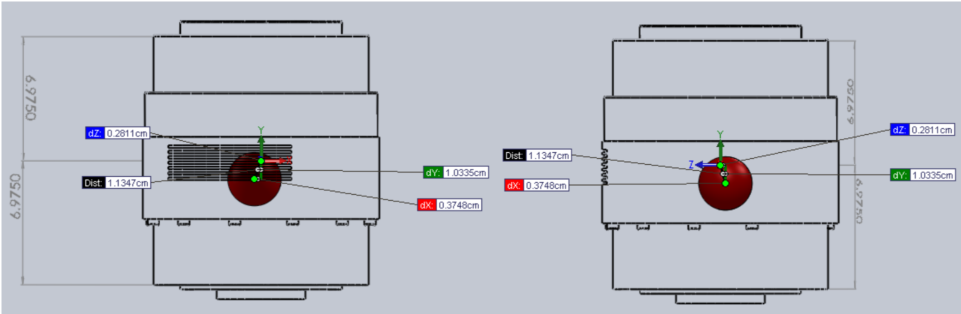


Figure 55: Torso Motor COM Visualization

16.15 Shoulder Bracket

The shoulder brackets are composed of a number of smaller pieces, the individual weight of each of which, is shown in figure 56. The total mass is $2.684kg$.

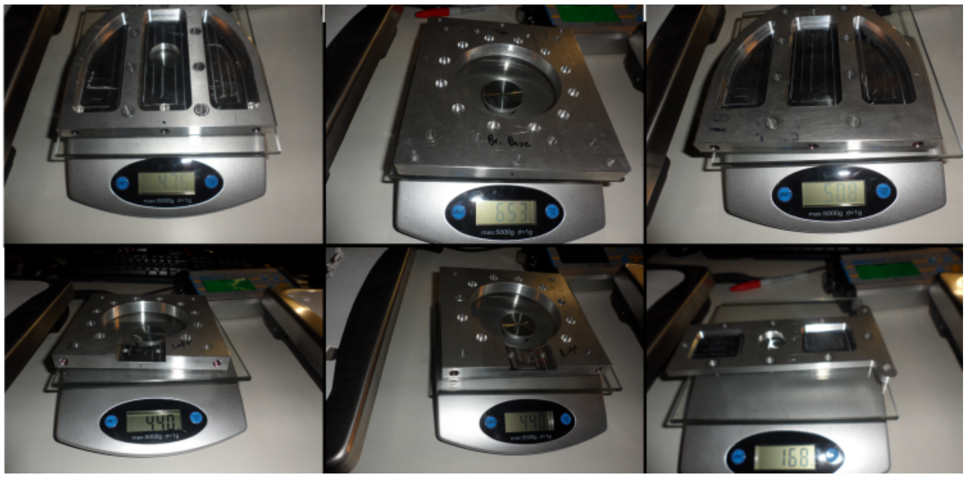


Figure 56: Mass measurements for shoulder bracket

Since the geometry is known and the material properties are assumed uniform, SolidWorks is used to determine the center of mass of the shoulder bracket. This is shown in figure 57. The center of mass is $(x, y, z)_{COM} = (0, 15.2927, -0.0036)cm$.

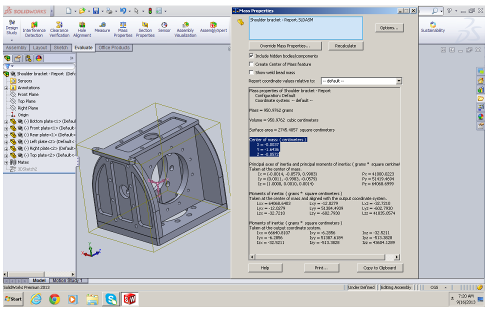


Figure 57: COM of shoulder bracket determined by SolidWorks

The center of mass estimated in SolidWorks is visualized in figure 58.

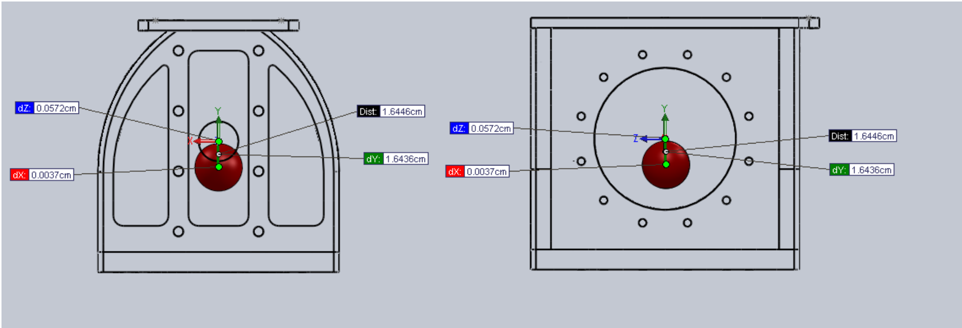


Figure 58: Visualization of COM of Shoulder Bracket

16.16 Kinect Holder

Kinect is mounted on an unactuated joint that is hinged to a base fixed on the bracket section. Figure 59 shows the mass measurement of this part. As shown in figure 8 the part origin is chosen to be at the center of the bottom surface of the holder. Due to symmetry the x-coordinates of the local COM is zero. As for the y- and z-coordinates, we did not perform measurements for the COM coordinates, we assigned a value of $1cm$ to the y-coordinate of the center of mass of this part and $-1.0cm$ to the z-coordinate. So the local center of mass is $(x, y, z)_{COM} = (0.0, 1.0, -1.0)cm$.

Figure 59: Mass measurement of kinect holder

16.17 Shoulder Bracket Screws

Figure 60 shows the mass measurements of the various screws used in the shoulder bracket. Table 22 lists down the individual masses.

Figure 60: Shoulder Bracket Screws masses A. Torso Screws (6 of 12) B. Long Screws (12 of 24) C. Kinect Screws D. Top Plate Screws E. Bottom Plate Screws

part	mass (kg)
Long Screws	0.132
Top Plate Screws	0.026
Bottom Plate Screws	0.019
Torso Screws	0.042
Kinect Screws	0.01

Table 22: Mass measurements of the screws in the shoulder bracket section

16.18 Arm

The mass measurments and local COMs of the entire arm will be discussed in this section, instead of going part by part.

16.18.1 Mass Measurements

In order to take the mass measurements, we took the left arm apart and measured the masses of all components on their weighing scale. Figure 61 shows the mass measurements. These measurements are listed down in table 23. In table 24, we distribute the mass of the long wires (figure 61P) that run throughout the length of the arm based on motor lengths. The wire mass estimated to be passing through each motor is used in respective section (e.g. Part entry "Wire through M1" in the "Arm Joint 1" section).

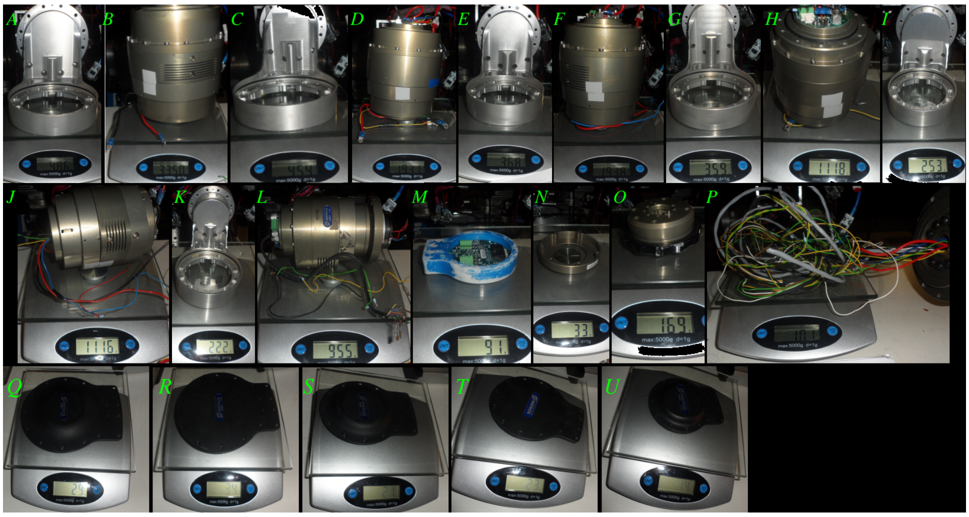


Figure 61: Mass measurements: A. C12 B. M2 C. C23 D. M3 E. C34 F. M4 G. C45 H. M5 I. C56 J. M6 K. C67 L. M7 + FT Sensor M. Netcan FT Card N. FT Cap O. FT Extension P. Wires Q. Cap (C12-M2) R. Cap (M2-C23) S. Cap (C34-M4) T. Cap (M4-C45) U. Cap (C56-M6)

Part	Mass (kg)
Motor M1	3.350
Motor M2	3.350
Motor M3	1.931
Motor M4	1.938
Motor M5	1.118
Motor M6	1.116
Motor M7 + FT Sensor	0.955
Connector Bracket C12	0.486
Connector Bracket C23	0.454
Connector Bracket C34	0.368
Connector Bracket C45	0.359
Connector Bracket C56	0.253
Cap C12-M2	0.029
Cap M2-C23	0.034
Cap C34-M4	0.021
Cap M4-C45	0.023
Cap C56-M6	0.014
Netcan FT Card	0.091
FT Cap	0.033
FT Extension	0.169
Wires	0.101

Table 23: Mass measurements of the left arm

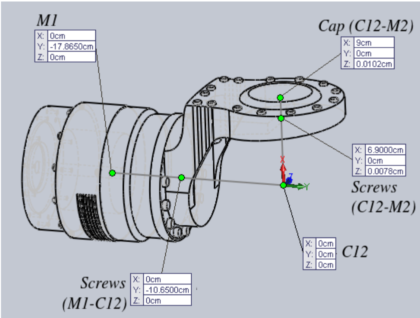
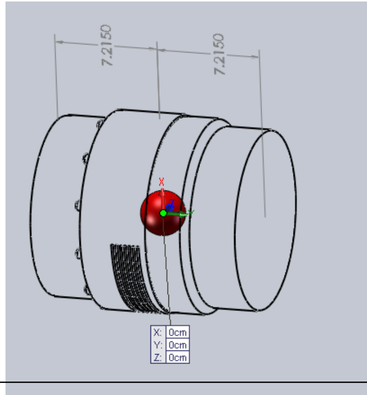
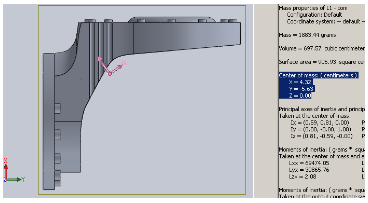
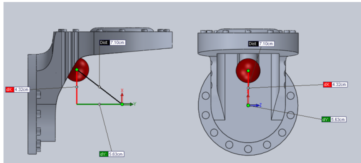
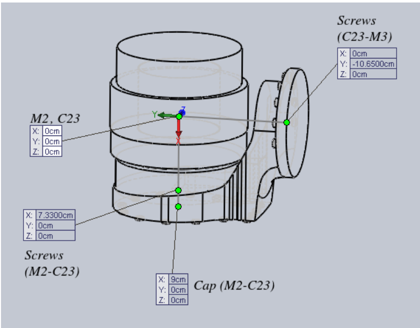
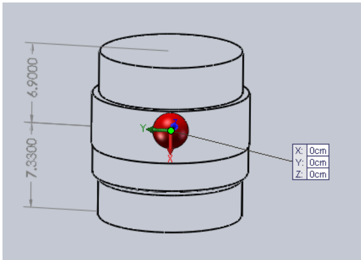
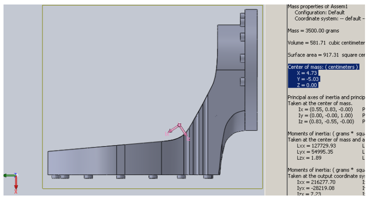
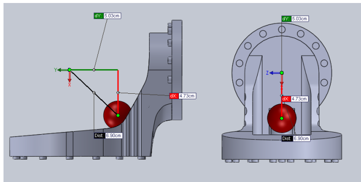
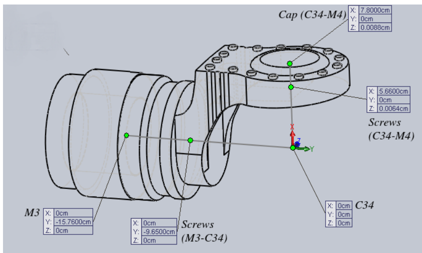
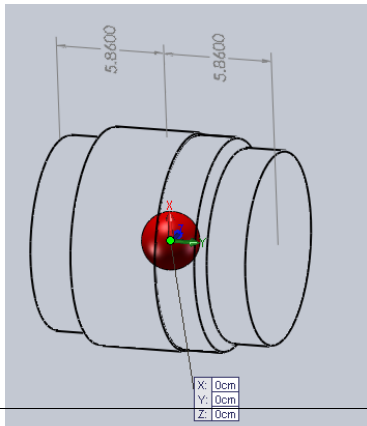
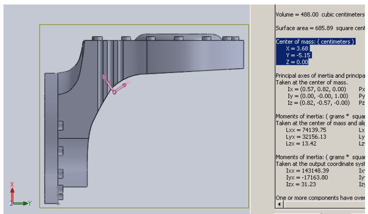
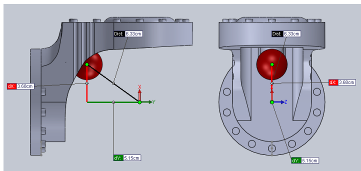
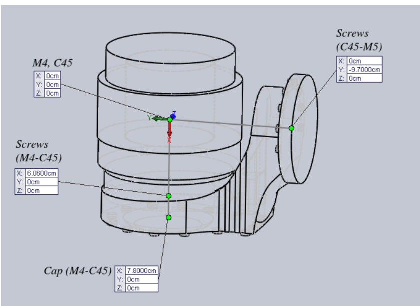
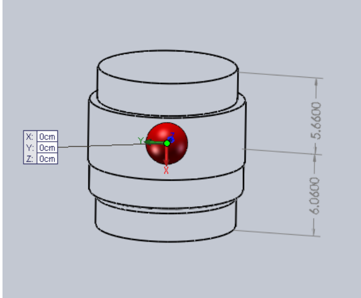
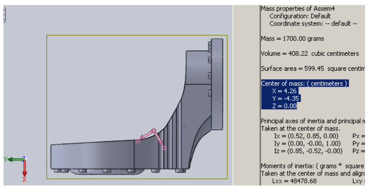
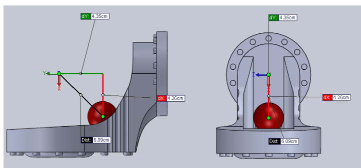
Motor	Motor Length (l_M) [cm]	Wire Mass through Motor ($m_W = \frac{l_M}{\sum l_M} \times \sum m_W$)[kg]
M1	14.43	0.0180
M2	14.23	0.0180
M3	11.72	0.0146
M4	11.72	0.0146
M5	9.98	0.0125
M6	9.98	0.0125
M7	8.61	0.0108
Total	80.67	0.101

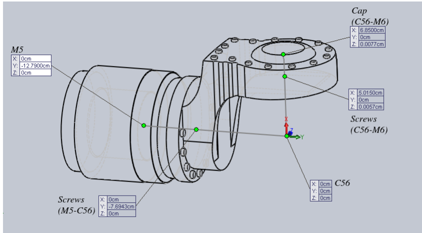
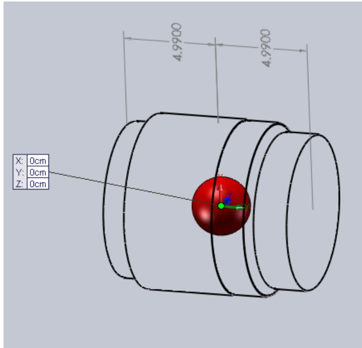
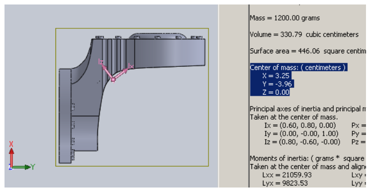
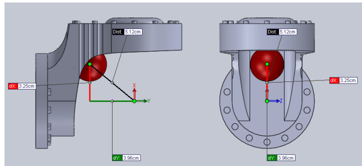
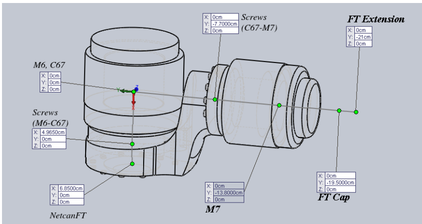
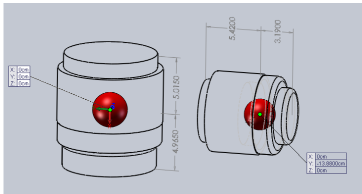
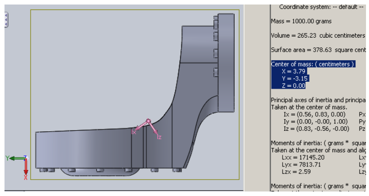
Table 24: Distributing Mass of Long Wires over the Arm

16.18.2 Local COMs

The local COMs of screws and caps are assumed to be at the part origins. For the motors, they are assumed to be at their geometric centers and for the brackets SolidWorks model is used to determine the local COM. Table 25 shows the part origins, motors' local COM visualization and solidwork estimate along with visualization of the connector brackets' local COMs.

Table 25: Arm COM measurement figures

Sec.	Section Origins	Motor COM Vis	Bracket COM
1			 
2			 
3			 
4			 

5	 Cap (C56-M6) M5 Screws (C56-M6) C56 Screws (M5-C56)	 4.9900 4.9900	 Mass = 1200.00 grams Volume = 330.79 cubic centimeters 
6	 Screws (C67-M7) FT Extension M6, C67 Screws (M6-C67) NetcanFT M7 FT Cap	 5.4200 3.1900 5.0150 4.9450	 Mass = 1000.00 grams Volume = 265.23 cubic centimeters